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Volcanology and Mineral Deposits

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John Wood and Henry Wallace**

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Cover: Photo of lava lake activity, Mount Nyiragongo, West African Rift Valley, Zaire. Photo taken by R.M. Easton, August 1972.

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Foreword

In December of 1982, during the annual Ontario Geoscience Seminar, the staff of the Precambrian Section of the Ontario Geological Survey conducted a half-day forum with the theme "Volcanology and Mineral Deposits".

This volume documents the presentations given at that seminar in an expanded form. The chapters included here are intended to remind geologists of basic principles and techniques employed in fields such as physical volcanology and volcanic stratigraphy, and to acquaint them with new developments in these areas that have significant implications for mineral exploration. Examples are taken from Ontario's Archean greenstone belts, and illustrate the types of work done by many Ontario Geological Survey geologists over the past several years. I hope that the reader will find this a useful aid and reference in these increasingly complex fields.

V.G. Milne
Director
Ontario Geological Survey



Introduction

Stratigraphy, lithologic parameters and structural features are fundamentally important controls known to influence the location and character of most types of mineral deposits. This volume deals with the interrelationship between these fundamental factors in volcanic terrains. Even though the emphasis here is on the discussion of volcanic stratigraphy and lithologies, it should be clear that a knowledge and understanding of structure are obligatory in describing and interpreting both mineral deposits and the rocks in which they occur. This maxim applies equally in the quest for new deposits, particularly in complex Archean terrain.

The purpose of this publication is to inform and interest the exploration geologist in a wide variety of topics related to volcanology, mineral deposits, and the geology of Ontario. Volcanology, like many other subdisciplines of geology, has become a multi-faceted, rapidly expanding field. In light of this, the first chapters included here introduce terminology commonly employed, and describe concepts, principles and techniques applied in the later chapters. Two of these principles, volcanic facies analysis and stratigraphic analysis are basic to understanding spatial and genetic relationships between volcanic rocks and mineral deposits.

Following the thematic chapters are a series which illustrate the use and utility of these techniques and concepts when applied to common problems of mapping and mineral exploration in Archean supracrustal belts. Mineral deposits in such areas as Timmins-Kirkland Lake, Wawa, Red Lake, and Lake of the Woods are placed within their stratigraphic context, and possible volcanological controls on their development are discussed.

The last two chapters in the volume differ from those outlined above in that they are concerned primarily with chemical characteristics of volcanic rocks which serve as useful clues in the search for mineral deposits. The first illustrates the significance of these related concepts in volcanology, namely volcanic cyclicity within volcanic environments and stratigraphic intervals of high mineral potential.

The last chapter deals with the use of statistical techniques which, when applied to lithogeochemical data, can help define the extent and character of alteration commonly associated with mineral deposits. These methods, used in conjunction with geological information, greatly enhance the geologist's ability to identify exploration targets from the mass of chemical data typically acquired during modern regional exploration programs.

This volume by no means provides an exhaustive coverage of our stated subject; we hope that for many it will serve as a useful introduction or reminder of what can be accomplished. Even though many of the cited examples of economic mineralization are base-metal deposits, it should be borne in mind that the ability to unravel volcanology and stratigraphy is fundamental to the understanding of the geology of any Archean greenstone belt, and hence is of immense value even in the search for structurally controlled deposits. For more information on the topics outlined; references are of course included in each of the chapters, and the geological staff of the Ontario Geological Survey are always available to those interested in discussing any aspect of Ontario's geology and mineral potential.



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CONVERSION FROM SI TO IMPERIAL			CONVERSION FROM IMPERIAL TO SI		
SI Unit	Multiplied by	Gives	Imperial Unit	Multiplied by	Gives
LENGTH					
1 mm	0.039 37	inches	1 inch	25.4	mm
1 cm	0.393 70	inches	1 inch	2.54	cm
1 m	3.280 84	feet	1 foot	0.304 8	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	1.609 344	km
AREA					
1 cm ²	0.155 0	square inches	1 square inch	6.451 6	cm ²
1 m ²	10.763 9	square feet	1 square foot	0.092 903 04	m ²
1 km ²	0.386 10	square miles	1 square mile	2.589 988	km ²
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
VOLUME					
1 cm ³	0.061 02	cubic inches	1 cubic inch	16.387 064	cm ³
1 m ³	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m ³
1 m ³	1.308 0	cubic yards	1 cubic yard	0.764 555	m ³
CAPACITY					
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	4.546 090	L
MASS					
1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	31.103 476 8	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	0.453 592 37	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	907.184 74	kg
1 t	1.102 311	tons (short)	1 ton (short)	0.907 184 74	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	1016.046 908 8	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	1.016 046 908 8	t
CONCENTRATION					
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t
OTHER USEFUL CONVERSION FACTORS					
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)			
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)			

Note. Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in cooperation with the Coal Association of Canada.

Part One: Concepts and Principles in the Study of Volcanoes and Volcanic Rocks

Chapter 1

Volcanology and Mineral Exploration: The Application of Physical Volcanology and Facies Studies

R.M.Easton and G.W.Johns

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ABSTRACT

Recognition of volcanic facies regimes in the Archean is a potential mineral exploration tool which can help discriminate between barren and mineralized environments. Recognition of volcanic facies requires the ability to classify Archean pyroclastic and volcanic fragmental rocks, and to identify, where possible, the eruptive and depositional mechanisms which produced these deposits. This chapter reviews the classification of volcanic fragmental rocks, the classification of facies models for volcanic sequences, and illustrates how these concepts can be applied in four Archean case studies with reference to their potential use in mineral exploration.

INTRODUCTION

Mineral deposits are anomalies, and Sangster (1980) has noted that massive-sulphide mining districts have an average diameter of 32 km; that is, an area of 800 km². Within this 800 km² area, a mineral deposit is still a very small target. Many massive-sulphide deposits are associated with volcanic rocks in what is commonly called a proximal volcanic environment. Identification and mapping of the physical character of volcanic rocks (physical volcanology) and their environment of deposition (facies analysis) will narrow the search area and make more efficient use of the exploration dollar.

RELATIONSHIP BETWEEN PHYSICAL VOLCANOLOGY AND MINERAL EXPLORATION

Physical volcanology can be related to mineral exploration in two ways. Firstly, it can be related to mineral exploration in an empirical sense, as is shown in Figure 1.1a. In this model of a typical Kuroko massive-sulphide deposit, there exists a physical association between lava domes, phreatic breccias, and ore. This association most commonly occurs in a proximal volcanic environment. Sangster (1972) has observed a similar association between coarse pyroclastic breccias, which he termed "mill-rock", and volcanogenic massive-sulphide deposits in the Superior Province of Ontario. Thus, exploration methods rely on the ability of the geoscientist to identify coarse pyroclastic breccias in proximal to vent environments in the search for such deposits.

Secondly, physical volcanology and mineral exploration can be related in a conceptual sense, as shown in Figure 1.1b. Here, physical volcanology and facies analysis have been used to develop models of ore genesis, as is shown in this example from the Kuroko region of Japan. Such models can then be used to outline areas of favourable mineral potential in other similar areas. Even though the Kuroko model for the genesis of massive-sulphide deposits was developed for a modern volcanic region, the model has been successfully applied to Archean mining camps (Franklin *et al.* 1981).

In both these cases, physical volcanology and facies analysis are tools which can be used in conjunction with other tools such as stratigraphic correlation and geochemistry to form the basis of mineral exploration programs (Trowell, Chapter 2, this volume). This, however, is a two-way process, for unless

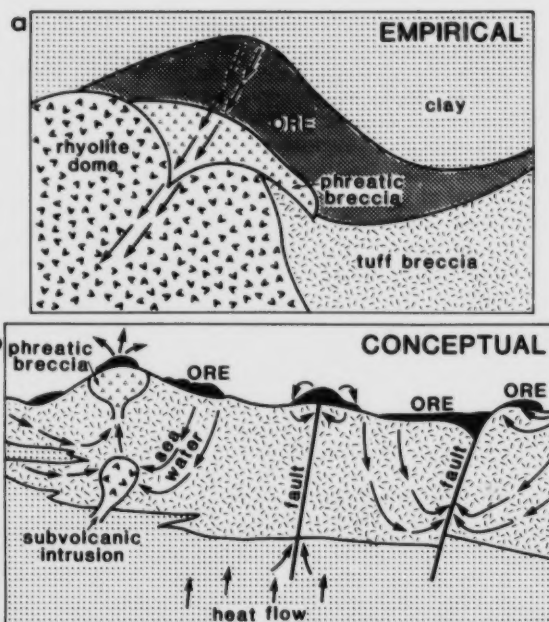


Figure 1.1. Relationship between physical volcanology and mineral exploration may be seen in an empirical or a conceptual sense. In an empirical sense (a), there is an observed association between ore and rock type. In a conceptual sense (b), a model is developed to explain the observed ore/rock associations. This model can then be used to explore for new deposits. Both examples shown are for the Kuroko massive-sulphide district, Japan (modified from Franklin *et al.* 1981). a) idealized cross section of a typical Kuroko deposit; b) essential features of recent genetic models for volcanic-associated deposits.

volcanic rocks found in association with known ore-deposits are well described and understood in terms of their eruptive mechanisms and environments of deposition, important associations between ore and particular rock types could be missed, making it difficult to deduce models for ore-genesis and exploration.

SCOPE OF CHAPTER

In this chapter the authors hope to:

1. provide an introduction to the types of volcanic eruptions and the products of these eruptions
2. provide an introduction to the classification of volcanic products
3. discuss criteria that can be used to distinguish different eruptive products, with emphasis on pyroclastic rocks

4. discuss volcanic facies, and how facies analysis of volcanic rocks can aid mineral exploration programs
5. present some examples of how physical volcanology can be applied to mineral exploration

In doing so, the authors hope to illustrate the utility, the limitations, and the application of physical volcanology studies in the Archean to aid mineral exploration.

The chapter is divided into three, semi-independent sections. The first section is a review of volcanic rock classifications, emphasizing field methods, the types of materials produced by volcanic eruptions, and their mode of emplacement. The second section examines facies models for volcanic rocks to the extent that is possible at present, because this subject is still in its infancy. The final section presents several examples from the Superior Province showing how facies analysis and physical volcanology can be used to narrow the search area for mineral deposits.

TERMINOLOGY

For the purposes of this chapter, the following terms are defined below:

Physical Volcanology can be defined as the study of the products of volcanic eruptions, eruptive mechanisms, and the landforms produced by volcanic eruptions. By definition, physical volcanology includes aspects of the physical character of eruption products and facies analysis (the focus of this chapter), stratigraphy (Trowell, Chapter 2, this volume), and the reconstruction of paleoenvironments (a goal of most geologic mapping).

A *facies* is a deposit or an eruptive unit, or part thereof, having distinct spatial and geometric relations and internal characteristics (Self 1982d).

A *facies model* is a generalized summary of the organization of the deposits in space and time. The model should be a "norm", a basis for interpretation, and a predictor of new geologic situations (Self 1982d).

Pyroclastic deposits/rocks is used in a broad sense, as recommended by the IUGS (Schmid 1981). Schmid (1981) defined a pyroclast as "being generated by disruption as a direct result of volcanic action"; pyroclastic deposits are assemblages of pyroclasts. Moreover, Schmid (1981) allowed pyroclastic deposits to contain as much as 25% by volume of epiclastic, organic, chemical, sedimentary, and diagenetic admixtures. Included in the term pyroclastic deposits are subaerial and subaqueous fall, flow, and surge deposits, lahars, subsurface, and vent deposits, hyaloclastites, intrusion and extrusive breccias, and diatremes.

PHYSICAL VOLCANOLOGY

TYPES OF VOLCANIC ERUPTIONS

Before the methods of classifying and subdividing volcanic products are discussed, it is necessary to review how volcanic rocks are produced. This is because eruptive mechanisms affect the physical character of volcanic products, how and where they

are deposited, and hence, their usefulness as an exploration tool. For example, in order to use Sangster's (1972) observation that coarse pyroclastic breccias ("mill-rock") are associated with massive-sulphide deposits as an exploration tool, it is necessary to know how such breccias are formed. In recent volcanic terrains, coarse pyroclastic breccias may form by a variety of mechanisms:

1. pyroclastic flow, including ignimbrites, "block-and-ash" flows
2. autobrecciation during flowage or extrusion of lava domes
3. phreatic eruptions
4. debris flows, including lahars, mudflows

Naturally, not all of these deposits are likely to be mineralized. Phreatic eruption breccias are believed to be the most closely associated with massive-sulphide deposits in the Archean (Hodgson and Lydon 1977; Franklin *et al.* 1981). Thus, if different volcanic breccias and their eruptive mechanisms can be distinguished, such knowledge can be used to reduce the size of the potential exploration area.

For the purposes of this chapter, three main eruptive mechanisms exist:

1. *Phreatic* (steam) eruptions result when meteoric water is vapourized with sufficient pressure to fracture and eject the confining rocks. Purely phreatic explosions expel no juvenile (magmatic) material.
2. *Phreatomagmatic* (Surtseyan) eruptions are produced by the interaction of ground or surface water and magma, and may eject much lithic (accidental or accessory) material as well as juvenile material.
3. *Magmatic* eruptions result from the ejection on surface of molten material, either in an explosive or an extrusive eruption. Magmatic eruptions are further divided into several types. These are named after volcanoes which typically produce eruptions of that type (Table 1.1). In order of increasing intensity, they are basaltic flood eruptions, Hawaiian eruptions, Strombolian eruptions, Vulcanian eruptions, Sub-Plinian eruptions, Plinian eruptions, and Ultra-Plinian eruptions. Further details on these eruption types are given in Macdonald (1972), Williams and McBirney (1979), and in Table 1.1. An individual volcano may exhibit one or more of these eruptive mechanisms during its lifetime.

ERUPTION PRODUCTS

The eruptive mechanisms cited above produce two broad classes of deposits:

1. *Extrusive Deposits*. These include lava flows and lava domes produced only during magmatic eruptions.
2. *Explosive/Pyroclastic Deposits*. These include fall, flow, and surge deposits, and other pyroclastic deposits which may be produced by all three types of volcanic eruptions.

TABLE 1.1: CLASSIFICATION OF VOLCANIC ERUPTIONS AND THE TYPES OF VOLCANIC PRODUCTS ASSOCIATED WITH EACH (MODIFIED FROM MACDONALD 1972).

ERUPTION TYPE	PHYSICAL NATURE OF THE MAGMA	CHARACTER OF EXPLOSIVE ACTIVITY	NATURE OF EFFUSIVE ACTIVITY	NATURE OF DOMINANT EJECTA	STRUCTURES BUILT AROUND VENT
Basaltic flood	Fluid	Very weak ejection of very fluid blebs; lava fountains	Voluminous wide-spreading flows of very fluid lava	Bombs and spatter; very little ash	Spatter cones and ramparts; very broad flat lava cones; broad lava plain
Hawaiian	Fluid	Weak ejection of very fluid blebs; lava fountains	Thin, often extensive flows of fluid lava, pillow lavas in submarine setting	Bombs and spatter, very little ash	Spatter cones and ramparts; very broad flat lava cones
Strombolian	Moderately fluid	Weak to violent ejection of past fluid blebs	Thick, less extensive flows of moderately fluid lava, flows may be absent	Spherical to fusiform bombs; cinder; small to large amounts of glassy ash	Cinder cones
Vulcanian	Viscous	Moderate to violent ejection of solid or very viscous hot fragments of new lava	Flows commonly absent; when present they are thick and stubby; ash flows rare	Essential, glassy to lithic, blocks and ash; pumice	Ash cones, block cones
Sub-Plinian	Viscous	Like Vulcanian	Domes and/or short very thick flows; may be absent, ignimbrites	Like Vulcanian	Ash and pumice cones, domes
Plinian	Viscous	Paroxysmal ejection of large volumes of ash, with accompanying caldera collapse	Ash flows, small to very voluminous; may be absent	Glassy ash and pumice	Widespread pumice lapilli and ash beds; generally no cone building
Phreatic	No magma	Weak to violent ejection of solid fragments of old rock, surge deposits, pyroclastic flow and fall	None	Accessory and accidental blocks and ash	Block cones; tuff cones, rings
Phreatomagmatic	Fluid to viscous	Violent ejection of solid or viscous hot fragments of new lava and solid fragments of old rock	Pyroclastic flow and surge deposits	Glassy ash, accessory and accidental blocks and ash	Tuff cones, tuff rings, maars

Figure 1.2. Relationship of landform to environment for basaltic volcanism. The figure reflects volcanism in 4 distinct environments; such as at varying elevations in an island system, with A being 500 m above sea level; B being 10 m above; C being 100 m below; and D being 1000 m below sea level. Eruptive mechanisms responsible for these landforms are: A, D - magmatic eruption; B, C - phreatic or phreatomagmatic eruptions, or both. (Modified from Wholetz and Sheridan 1983).

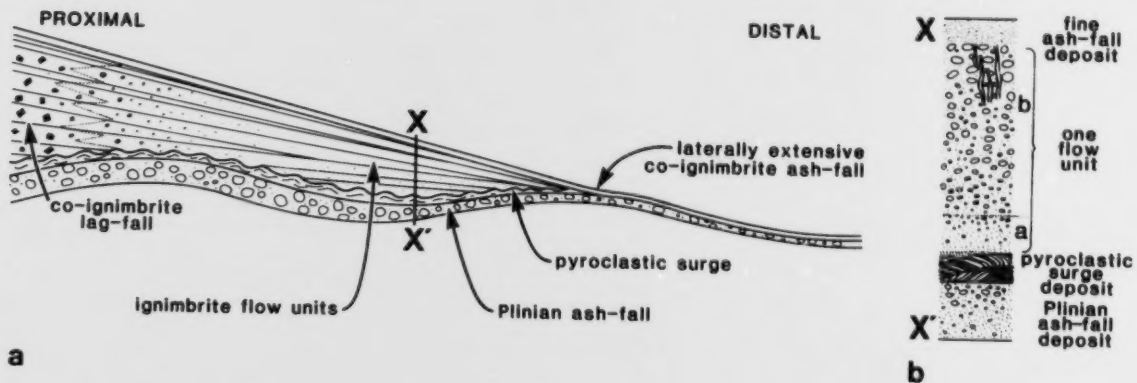
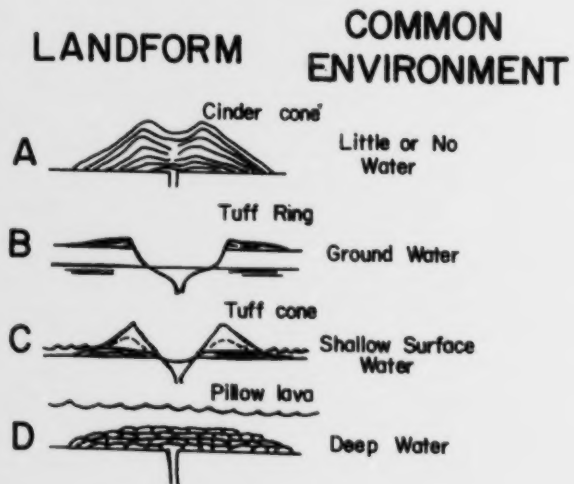


Figure 1.3. a) Facies model for pyroclastic deposits resulting from a medium- to large-scale silicic explosive eruption in a subaerial environment. X-X' denotes cross section shown in b. After Wright et al. (1981). b) Schematic diagram showing the deposits of an explosive silicic eruption. An inversely graded Plinian ash-fall bed is overlain by a surge deposit. The basal layer of the pyroclastic flow unit (a) may show inverse grading, whereas in the main part of the flow (b), lithic inclusions (filled clasts) are concentrated near the base, and pumice fragments (large open clasts) and fumarolic pipes are concentrated near the top of the flow. Deposits of fine co-ignimbrite ash occur above the flow unit. A lava flow may cap the sequence, which reflects eruption of increasingly volatile-poor magma. (After Self 1982a, 1982b and Sparks et al. 1973).

Some important factors which influence the type of volcanic products involved in any one eruption are:

1. **Environment.** For example, a subaerial magmatic eruption may produce a pahoehoe, aa, or block lava flow of andesitic composition, but a subaqueous eruption of the same magma will produce a pillowed flow, perhaps with associated pillow-breccia and hyalotuff. Indeed, the amount
2. **The Flow Unit Concept.** In many cases, a flow, either of lava or a pyroclastic flow, may be composed of a variety of distinct rock types. All of these rock types constitute a flow unit, and are the product of a single eruptive event. An exam-

of water-magma interaction, which may be indirectly related to water depth, can have a significant effect on the types of volcanic products erupted as shown in Figure 1.2.

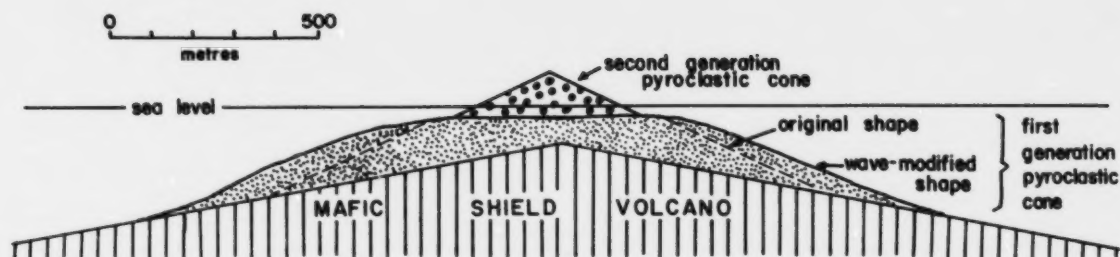


Figure 1.4. Model of an Archean island volcanic system. Second generation felsic to intermediate pyroclastic cone has been constructed atop an earlier wave-modified pyroclastic cone. Both are constructed atop a mafic shield volcano. Most volcanic products of the second cone are erupted subaerially, but are deposited, or redeposited subaqueously. (After Ayres 1982).

ple of this can be seen in the ash-flow deposit shown in Figure 1.3. Recognition of flow units is important in recognizing volcanic facies, reconstruction of paleoenvironments, and eruptive mechanisms, as discussed in later sections.

3. **Facies.** The facies regime of a particular deposit being studied has an effect on the volcanic products observed. Figure 1.3 is a facies model for a subaerial pyroclastic flow. The cross section shown in Figure 1.3b is what a deposit in the proximal facies of the flow would resemble. A deposit in the distal facies (Figure 1.3a) would consist of only the Plinian ash-fall deposit and the co-ignimbrite ash-fall, and may not be readily recognized as part of a pyroclastic flow deposit. Near the vent, a co-ignimbrite lag deposit would be present interfingering with the main part of the pyroclastic flow. Thus, an approximate idea of what facies regime the deposits under study may be in is required in order to accurately interpret the depositional mechanisms that formed the rocks under study.
4. **Island Systems.** Ayres (1982) has argued that many Archean volcanic systems, especially the mafic-felsic systems, were islands (Figure 1.4). In this case, most products may be erupted subaerially after a certain point in the evolution of the volcanic edifice has been passed. Most products, however, will be deposited subaqueously, either through primary deposition, or through reworking and redeposition. This is an important concept when it comes to the application of studies of modern volcanoes (mainly subaerial) to Archean volcanism.

VOLCANIC ROCK CLASSIFICATION

Now that we are aware of how volcanic rocks are produced, how do we classify such rocks, and how do we distinguish between different kinds of volcanic products, in particular explosive (pyroclastic) deposits?

Even though in this chapter, volcanic rocks are separated into two groups, extrusive rocks and volcanic fragmental (explosive) rocks, the reader should

be aware that the two are commonly intimately intermixed. In this chapter, emphasis is placed on the mesoscopic and microscopic lithological features of volcanic rocks, and not on the classification of volcanic rocks on the basis of chemistry.

Extrusive Rocks

Extrusive volcanic rocks are classified mainly on the basis of grain size, primary textures, structures, and flow morphology. Salient points of such classifications are listed below:

Grain Size Classification A commonly used system is that of Moorhouse (1959):

- Aphanitic: grains not visible with a hand lens
- Fine grained: <1 mm
- Medium grained: 1 to 5 mm
- Coarse grained: >5 mm

Textures Most standard igneous petrology texts define common textural terms (for example: Joplin 1968; Williams *et al.* 1954; Harker 1962; Macdonald 1972), and hence these are not repeated here. Some textures, however, may be diagnostic of individual flows or flow units; or of the specific chemical composition and flow type (for example, spinifex texture in ultramafic flows).

Structures Many flows in the Archean are mapped on the basis of internal structures, or lack of structures as in the case of massive flows. Some of the more important structures are discussed as follows:

Pillow Lavas. Pillow lavas are common throughout Archean volcanic terrains. Features to note in describing pillow lavas include the following:

1. size and shape
2. amygdaloidal or non-amygdaloidal
3. variolitic or non-variolitic
4. selvage thickness and possible differences in chemistry from the interior outward
5. internal structure, for example, radial, concentric

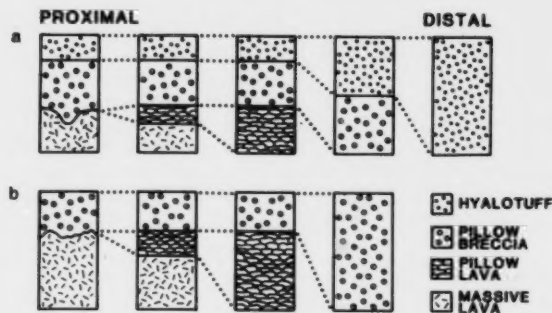


Figure 1.5. Two types of facies variation observed in subaqueous basalt and andesite flows. Each column represents a flow unit, and is composed of varying proportions of hyalotuff, pillow breccia, pillow lava, and massive lava. (Modified from Dimroth et al. 1978). For complete range of possible flow unit variation, see Dimroth et al. (1978).

6. packing relations, possible top determinations
7. amount and type of interpillow material

Dimroth et al. (1978, 1979), Dimroth and Rocheleau (1979), and Wells et al. (1979) have described how features such as size and shape and packing relations can be used to map out pillowed flows, and have developed a facies concept for pillowed flows (Figure 1.5; see Facies Section).

Moore et al. (1971) pointed out some of the dangers in making top and thickness determinations of ancient pillow lavas because the bedding plane measured may actually be from foreset beds on an initially steep slope. Borradaile (1982) has also examined how deformation can affect the accuracy of top determinations in pillowed volcanic sequences. In shallow dipping pillow lava sections, the accurate determination of facing directions may not be possible because of the shallow-angle of the exposed plane through the sequence.

Vesicles and Amygdules. A vesicle is a cavity of variable shape in a lava which is formed by the entrapment of a gas bubble during solidification of the lava (AGI 1980). An amygdale is a gas cavity or vesicle in an igneous rock which is filled with such secondary minerals as calcite, quartz, chalcedony, or a zeolite (AGI 1980).

In a study of vesicles in pillow lavas, Jones (1969) concluded that the size of vesicles (amygdules in most Archean flows) were related to water depth, that is, the deeper the water, the smaller the vesicles. The maximum water depth of vesicle formation is about 2000 m. Higgins (1971) arrived at the same conclusions. Moore (1970) noted that alkaline basalts are more vesicular than tholeiitic basalts that have been erupted at the same water depth. Note that vesicle size and abundance is a measure of the depth of emplacement, not necessarily the depth of eruption (Jones 1969). Vesicles also occur

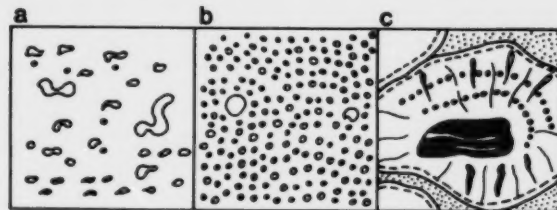


Figure 1.6. Vesicle shape and distribution in: a) aa; b) pahoehoe; and c) pillowed lava flows.

in subaerial flows; aa flows and pahoehoe flows have characteristic vesicle shape and size and abundance (Macdonald 1972; Figure 1.6), and can be used to distinguish between the two flow types. Features that should be noted in the field pertaining to vesicles and amygdules include the following:

1. size and variation in size: possible indication of flow type, or relative water depth
2. shape: spherical, elongate, deformed
3. filling: mineralogy, variation if any
4. distribution in pillows, sometimes concentrated at pillow top

Varieties and Variolitic Lavas. Varieties are pea-sized spheres, usually composed of radiating crystals of plagioclase or pyroxene. This term is generally applied only to these spherical bodies in basic igneous rocks (AGI 1980). A *spherulite* is a rounded or spherical mass of acicular crystals, commonly composed of feldspar, radiating from a central point (AGI 1980).

Varieties are common in Archean mafic lavas, and have been used in tracing individual flows and packages of flows in Archean "greenstone belts". The origin of varieties has been a subject of controversy (Carstens 1963; Furnes 1973; Gelinis et al. 1976; Hughes 1977; Philpotts 1977; Dimroth and Rocheleau 1979). There are probably two varieties of varieties: those formed by devitrification processes; and those formed by spherulitic crystallization of immiscible silicate globules.

Melson and Thompson (1973) and Furnes (1973) have noted that varieties have been found in basalts dredged from the ocean floor at depths of 1600 to 5000 m. Amygdules, which are known to form in water depths of <2000 m, have also been reported in variolitic flows. In pillow lavas, Dimroth and Rocheleau (1979) noted three types of variole distribution:

1. rim type which is close to the inner chill margin in a zone up to 15 cm thick
2. central type which is close to the pillow core, margins may be variole-free
3. random type

Varieties have also been observed in hyaloclastite units (Dimroth and Rocheleau 1979; Furnes 1973).

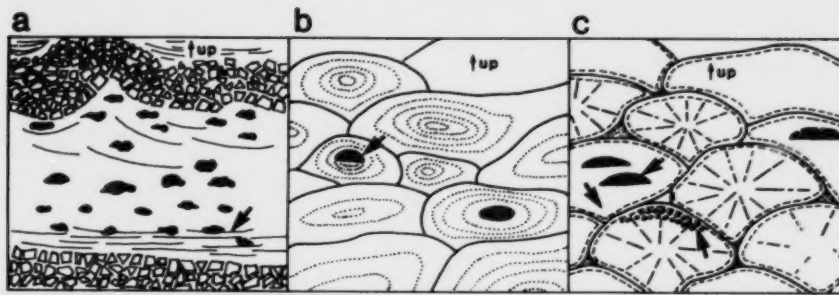
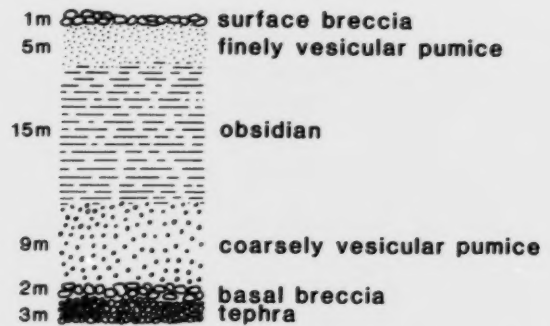
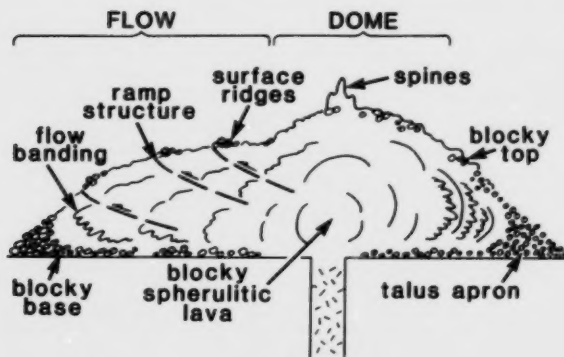


Figure 1.7. Flow morphology in aa (a), pahoehoe (b), and pillowed (c) lava flows as seen in cross section. Arrows indicate top indicators commonly found in the flows. Dark areas represent voids.



a

b

Figure 1.8. a) Schematic cross section through an endogenous dome and flow of viscous lava. (After Self 1982c). b) Schematic cross section through a rhyolitic obsidian flow. Compare with mafic flow cross section shown in Figure 1.7a. (After Self 1982c).

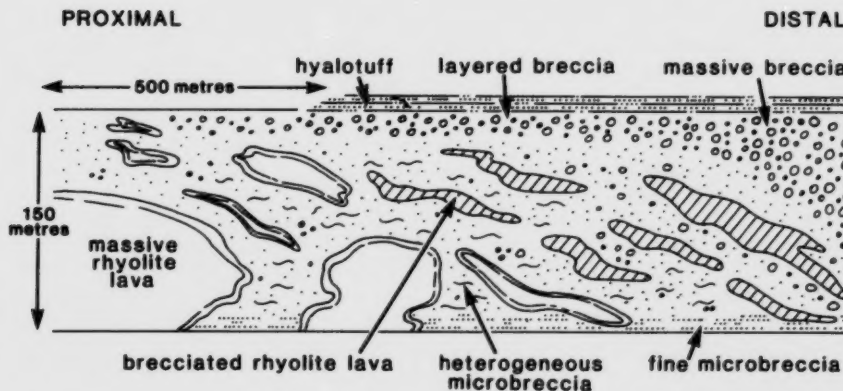


Figure 1.9. Structure of an Archean subaqueous rhyolite flow from Rouyn-Noranda, Quebec. (Modified from Dimroth and Rocheleau 1979). Compare with mafic flows shown in Figure 1.5.

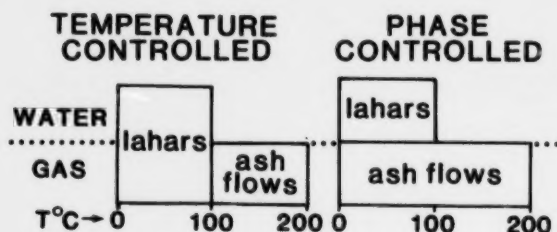


Figure 1.10. Illustration showing the inherent classification problems with some pyroclastic rocks. Note the difference in the fields for ash flows and mudflows (lahars) according to whether temperature (left) or the nature of the continuous phase (liquid water or gas) (right) is regarded as more important. (Adapted from Walker 1981).

Flow Morphology Flow morphology refers to the constitution of an individual flow unit. Differences in flow morphology can be seen in Figure 1.7, where the morphology of an aa, pahoehoe, and pillowed flow are compared. In addition, flow morphology may show lateral variations, such as is shown in the pillowed flows shown in Figure 1.5. These lateral variations may be related to a facies model, as in the case of pillowed flows (Dimroth *et al.* 1978, 1979; see Facies Section). In addition, lava domes and flows of felsic and intermediate composition have morphology different from mafic extrusive rocks (compare Figure 1.7 with Figure 1.8). Pillow lavas are restricted to andesitic or more mafic lavas, but a modern pillow composed of dacite has been reported at one locality (Macdonald 1972). The pillow formation in that case was ascribed to an unusually high volatile content. Although pillowed structures are not normally found in felsic and intermediate flows, Dimroth and Rocheleau (1979) and de Rosen-Spence *et al.* (1980) suggested that subaqueous rhyolite and dacite flows behaved much the same as their more mafic counterparts. These flows consist of a massive core overlain by fine breccia and hyalotuff derived from the flow near the vent, and consist of breccia and hyalotuff distal to the vent (Figure 1.9).

Lava domes may occur in both vent and proximal areas, and may precede or follow large-scale caldera collapse. Lava domes do not indicate a waning of volcanic activity as was previously considered (Newhall and Melson 1983). In addition, lava domes can be associated with phreatomagmatic eruptions, and can occur in a number of volcanic environments. Lava domes may have associated lava flows, that can form by breaching of the dome and outflow. Morphology of lava domes in subaerial and subaqueous environments is probably similar, although more breccia and hyalotuff may be present with the latter. Domes may also be associated with pyroclastic flows, either directly, as in the case of pyroclastic flows generated by dome collapse, or indirectly, as in the association with post-caldera collapse volcanism. As discussed by Thurston (Chapter 7, this volume),

lava domes associated with caldera collapse may be mineralized. Domes may also occur as shallow-level, subsurface intrusions.

Several zones are commonly developed within lava domes and flows, and are labelled in Figures 1.8a and 1.8b, respectively. Descriptions of lava domes are given in Macdonald (1972), Williams and McBirney (1979), and Self (1982c), and of viscous lava flows in Christiansen and Lipman (1966), Fink (1980), Self (1982c), and Macdonald (1972).

Volcanic Fragmental Rocks

The classification of volcanic fragmental rocks presented herein is based on the classification schemes of Schmid (1981) and Wright *et al.* (1980), as well as the work of Fisher (1966), Parsons (1969), Schmincke (1974), and Dimroth (1977). Volcanic fragmental rocks are classified on the basis of the method of fragmentation, grain size, and fragment composition (Schmid 1981). These rocks can also be classified on the basis of the method of emplacement, as is the case for many modern volcanic fragmental rocks (Wright *et al.* 1980).

Type of Fragmentation Autoclastic Rocks. Fragmentation is due to mechanical deformation where different parts of a flow or dome differ in viscosity. Flowage will cause the less viscous parts of the flow to deform plastically, whereas the outer more brittle parts which are cooler than the interior will fracture.

Pyroclastic Rocks. Fragmentation is related to either magmatic, phreatomagmatic, or phreatic eruptions, as was discussed earlier. In addition, fragmentation may also occur due to rapid chilling of hot magma with water, causing shattering of the magma with no explosive activity producing hyaloclastic rocks.

Alloclastic Rocks. These rocks are formed by the fragmentation of pre-existing rocks by subsurface volcanic processes, such as intrusion (Wright and Bowes 1963). Under the IUGS classification scheme (Schmid 1981), these rocks are pyroclastic rocks, as their origin is directly related to volcanic action. Alloclastic rocks are typically found in eroded volcanic vents and show crosscutting relationships.

Redeposited Fragmental Rocks. This is an important subcategory of volcanic fragmental rocks, that does not neatly fit into a classification system based on the fragmentation mechanism. These rocks consist entirely of volcanic material, and many form by direct volcanic action (Crandell 1971), and hence, are pyroclastic rocks as defined by the IUGS (Schmid 1981). These deposits include debris avalanche and debris flow deposits, of which lahars are an important subset. These rocks pose many difficulties in terms of classification, partly because of the various usages of the terms in the past, and inherent classification problems as are shown in Figure 1.10. Because of the confusion surrounding terms such as lahar, a brief discussion of these rocks is warranted. The following definitions are used in this chapter, and follow the usage of Fisher (1982b) and Lipman and Mullineaux (1981).

A *debris avalanche* is the result of the very rapid and usually sudden sliding and flowage of incoher-

ent, unsorted mixtures of soil and bedrock (AGI 1980).

A *debris flow* is a moving mass of rock fragments, soil, and mud. More than half of the particles are larger than sand size (2 mm) (AGI 1980). *Mud flow* should be restricted to debris flows consisting dominantly of mud (that is, >50% sand, silt, and clay) (Fisher 1982b; Sharp and Nobles 1953). A *lahar* is a special class of debris flow composed of volcanic particles (Fisher 1982b). A lahar may consist of mainly mud (ash), and may grade into mudflows with increasing distance from the vent. Not all lahars form as a direct result of volcanic activity (Crandell 1971; Table 1.2), and technically, not all lahars are pyroclastic rocks. In practice, it is not always possible to determine the origin of an Archean lahatic deposit. Thus, if such a deposit is composed of <25% epiclastic material, it is commonly considered a pyroclastic rock. Table 1.3 compares the characteristics of other coarse-grained volcanic fragmental rocks with lahars. Subaqueous lahars are believed to be similar to subaerial lahars (Fisher 1982b).

Grain Size Classification Grain size limits of pyroclasts are comparable to the grain size limits used by sedimentologists, as is shown in Figure 1.11. These size limits apply to autoclastic, pyroclastic, alloclastic, and hyaloclastic rocks, as well as to debris flows. The terms for unimodal, well-sorted pyroclastic rocks (Figure 1.11; Schmid 1981) are described below:

TABLE 1.2: ORIGIN OF LAHARS (AFTER CRANDELL 1971).

- I. **DIRECT AND IMMEDIATE RESULT OF ERUPTION**
 1. Eruption through crater lake, snow, or ice.
 2. Heavy rain during an eruption.
 3. Flow of hot pyroclastic material into rivers or onto snow or ice.
- II. **INDIRECTLY RELATED TO AN ERUPTION**
 1. Triggering of water-soaked debris by earthquake.
 2. Bursting and rapid drainage of crater lakes.
 3. Dewatering of large avalanches originating from collapse of volcano side.
- III. **NOT RELATED TO CONTEMPORANEOUS VOLCANIC ACTIVITY**
 1. Mobilization of loose tephra by rain or meltwater.
 2. Collapse of unstable clay- and water-rich debris.
 3. Bursting of dams from overloading.
 4. From volcanoes or volcanic terrains undergoing active weathering and erosion.

TABLE 1.3: COMPARISON OF OTHER COARSE-GRAINED DEPOSITS WITH LAHARS (AFTER FISHER 1982b).

	LAHARS	TILL (EXCLUDING WATER-LAID TILL)	UNWELDED IGNIMBRITE	FLUVIAL DEPOSITS
Large fragments (>2 mm)	May have boulders weighing many tons.	May have boulders weighing many tons.	Extremely large boulder absent.	Extremely large boulders rare.
Sorting	Poor. May contain abundant clay-size material.	Poor. May contain abundant clay-size material.	Poor. Clay-size material rare or absent.	Poor. Clay-size material sparse.
Grading	Commonly reversed. May be normal or absent.	Commonly absent.	Commonly absent, but may be normal or reverse.	Commonly normal.
Bedding and thickness	Commonly very thick with vague internal bedding.	Very thick. No bedding.	Commonly very thick with vague internal layering.	Thin with channels and crossbeds.
Composition	Commonly 100% volcanic. May be pyroclastic or mixed with epiclastic materials. May contain breadcrust bombs.	Commonly heterolithic and mostly non-volcanic materials. Epiclastic	Pyroclastic. May contain abundant breadcrust bombs.	Material usually 100% epiclastic.
Rounding of large fragments	Commonly angular to subangular.	Commonly subangular to subrounded. May be faceted.	Commonly subangular.	Commonly subrounded to rounded.
Pumice	Common in some lahars.	Not present.	Common.	Not present.
Lower surfaces	Commonly not erosional	Commonly erosional.	Commonly not erosional.	Erosional.

UNCONSOLIDATED DEPOSITS			CONSOLIDATED	
SIZE mm	EPICLASTIC	PYROCLASTIC		
256	BOULDERS	Coarse	BLOCKS or BOMBS	BRECCIA
	COBBLE	Fine		
64	PEBBLE	LAPILLI		LAPILLI- TUFF
2	SAND	Coarse	ASH	TUFF
1/16	SILT	Fine		
1/256	CLAY			

Figure 1.11. Granulometric classification for unimodal, well sorted pyroclastic rocks, both unconsolidated and consolidated. Terms for epiclastic rocks are shown for comparison.

A *pyroclastic breccia* is a pyroclastic rock whose average pyroclast size exceeds 64 mm and in which angular pyroclasts (blocks) predominate. If rounded, aerodynamically shaped pyroclasts predominate (Photo 1.1), then the rock is termed an agglomerate. Table 1.4 is a classification of pyroclastic breccias based on the type of fragmentation.

A *lapilli-tuff* is a pyroclastic rock whose average pyroclast size is 2 to 65 mm.

A *tuff* is a pyroclastic rock whose average pyroclast size is <2 mm.

Polymodal or poorly sorted pyroclastic rocks containing pyroclasts of more than one dominant size fraction can be named by using an appropriate combination of the terms which are given above, and are also given in Figure 1.12 (Schmid 1981). For some field areas, additional subdivisions can be made, as illustrated in Figure 1.13. Figure 1.13 represents a modification of Fisher's (1966) classification, and has been made consistent with the IUGS terminology. Boundaries between rock types are based on the ease of use in the field when detailed granulometric analysis is not possible.

Terms for mixed pyroclastic-epiclastic rocks are listed in Table 1.5.

Fragment Composition and Shape Observation of fragment shape can give clues to the mechanism of fragmentation and to the eruptive processes involved. Roundness classes used in sedimentary rock descriptions can also be applied to volcanic fragments. Rounding of vesicular and pumiceous fragments may, however, occur very rapidly and with only minor transport when compared to sedimentary environments. The specific shapes of fragments, fine shards, and crystals can all aid in understanding the mode of formation of volcanic fragmental rocks

TABLE 1.4: SOME TYPES OF VOLCANIC BRECCIAS (AFTER PARSONS 1969).

- I. **Autoclastic volcanic breccias**
 - A. Friction breccias
 1. Flow breccias, by autobrecciation of lavas
 2. Crumbling of plugs, domes, and spines
 - B. Explosion breccias (disruption by gas explosion)
- II. **Pyroclastic breccias**
 - A. Vulcanian breccias: aerial ejection by explosive eruption
 1. Breccias by strombolian and lava-fountain eruptions
 - B. Pyroclastic-flow breccias
 - C. Hydrovolcanic breccias
 1. Breccias formed by phreatic eruptions
 2. Laharic breccias (volcanic-mudflow deposits)
 3. Hyaloclastic breccias (hyaloclastites)
 - D. Vent agglomerates and vent breccias
- III. **Alloclastic volcanic breccias**
 - A. Intrusion breccia (caused by intrusion of magma)
 - B. Explosion breccias
 - C. Intrusive breccias (show crosscutting relationships)
- IV. **Epiclastic volcanic breccias**
 - A. Laharic breccias (in part)
 - B. Water-laid volcanic breccias

(Figures 1.12 and 1.13), as will be discussed later in more detail.

Fragment composition is also an important criteria in the classification of volcanic fragmental rocks (Figures 1.12 and 1.13). Three sources of fragments may be found in volcanic fragmental rocks, as follows:

1. essential or juvenile fragments: particles of cooled magma
2. accessory fragments: solidified volcanic rocks from previous eruption
3. accidental fragments: broken solid country rock

In addition, the proportion of rock fragments to crystals to glass shards can be used to classify tuffs (Figure 1.12).

Method of Emplacement Wright *et al.* (1980) proposed a working classification for pyroclastic rocks on the basis of depositional/eruptive mechanism. This classification, unlike that of Schmid (1981) and Fisher (1966) is genetic in character, and hence, cannot always be applied to Archean volcanic rocks.

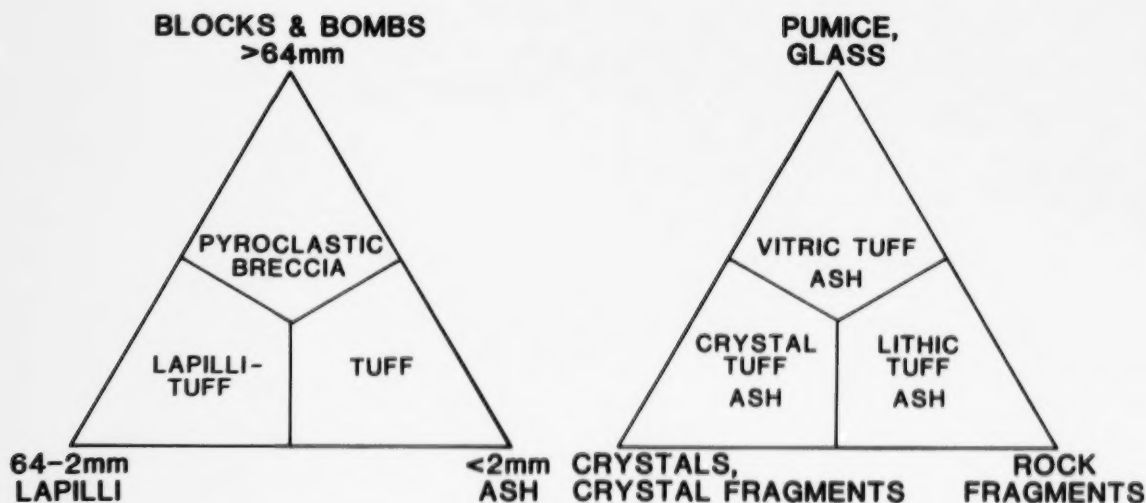


Figure 1.12. Granulometric classification of pyroclastic deposits (left) and subdivision of tuffs and ashes according to their fragmental composition (right).

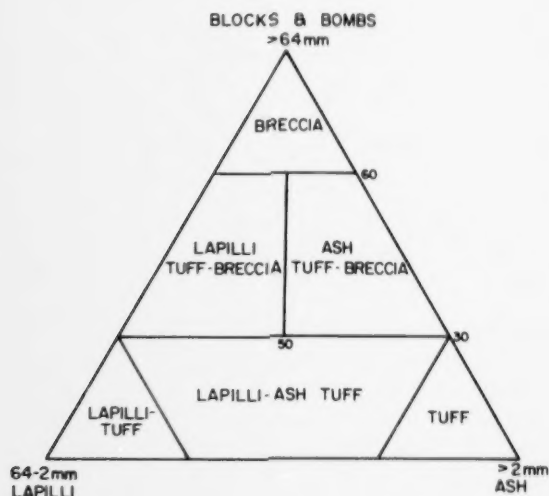


Figure 1.13. Granulometric classification for poly-modal volcanic fragmental rocks where a more detailed classification than shown in Figure 1.12 is needed. (Adapted from Schmid 1981 and Fisher 1966). The term tuff-breccia would include lapilli- and ash-tuff breccia.

Nevertheless, it has utility in understanding recent pyroclastic deposits, and in interpreting the mechanisms that may have produced Archean pyroclastic deposits.

Wright *et al.* (1980), following Sparks and Walker (1973), recognized three basic types of pyroclastic deposits (see Figure 1.15, Table 1.6):

1. **Pyroclastic Fall Deposits.** These are produced when material is explosively ejected from the vent forming an eruption column. Fall deposits show mantle bedding (Photo 1.1, Figure 1.14), maintaining a uniform thickness over restricted areas while draping all but the steepest topography. The deposits are generally well sorted. Although Wright *et al.* (1980) only discussed air-fall deposits, fall deposits may also form by settling through water, either from a subaerial, or a subaqueous eruption column.
2. **Pyroclastic Flow Deposits.** Pyroclastic flows involve the lateral movement of pyroclasts as a gravity-controlled, hot, high concentration gas/solid dispersion (Wright *et al.* 1980). Deposits are topographically controlled in high-aspect ratio flows (average thickness versus horizontal dimension, Walker 1983), and fill valleys and depressions. In contrast to fall deposits these flows are poorly sorted. Low aspect-ratio flows are controlled by topography only in a minor way.
3. **Surge Deposits.** Pyroclastic surges involve the lateral movement of pyroclasts as expanded, turbulent, low-concentration gas/solid dispersions (Wright *et al.* 1980). Deposits mantle topography, but accumulate in depressions (Figure 1.15). Surge deposits are most commonly associated with phreatomagmatic eruptions. Such deposits are often thin, and near-vent; hence, in terms of

TABLE 1.5: TERMS FOR MIXED PYROCLASTIC-EPICLASTIC ROCKS (AFTER SCHMID 1981).

Pyroclastic	Tuffites (Mixed Pyroclastic-Epiclastic)	Epiclastic (Volcanic and/or Nonvolcanic)	Average Clast Size (mm)
Agglomerate, agglutinate pyroclastic breccia	Tuffaceous conglomerate	Conglomerate, breccia	64
Lapilli-tuff	Tuffaceous breccia		
(Ash) tuff	Tuffaceous sandstone	Sandstone	2
coarse			
fine	Tuffaceous siltstone	Siltstone	1/16
	Tuffaceous mudstone, shale	Mudstone, shale	1/256
100-75% by volume	Pyroclasts	25-0%	
0-25% by volume	Volcanic + nonvolcanic epiclasts (+ minor amounts of biogenic, chemical sedimentary and authigenic constituents)	75-100%	

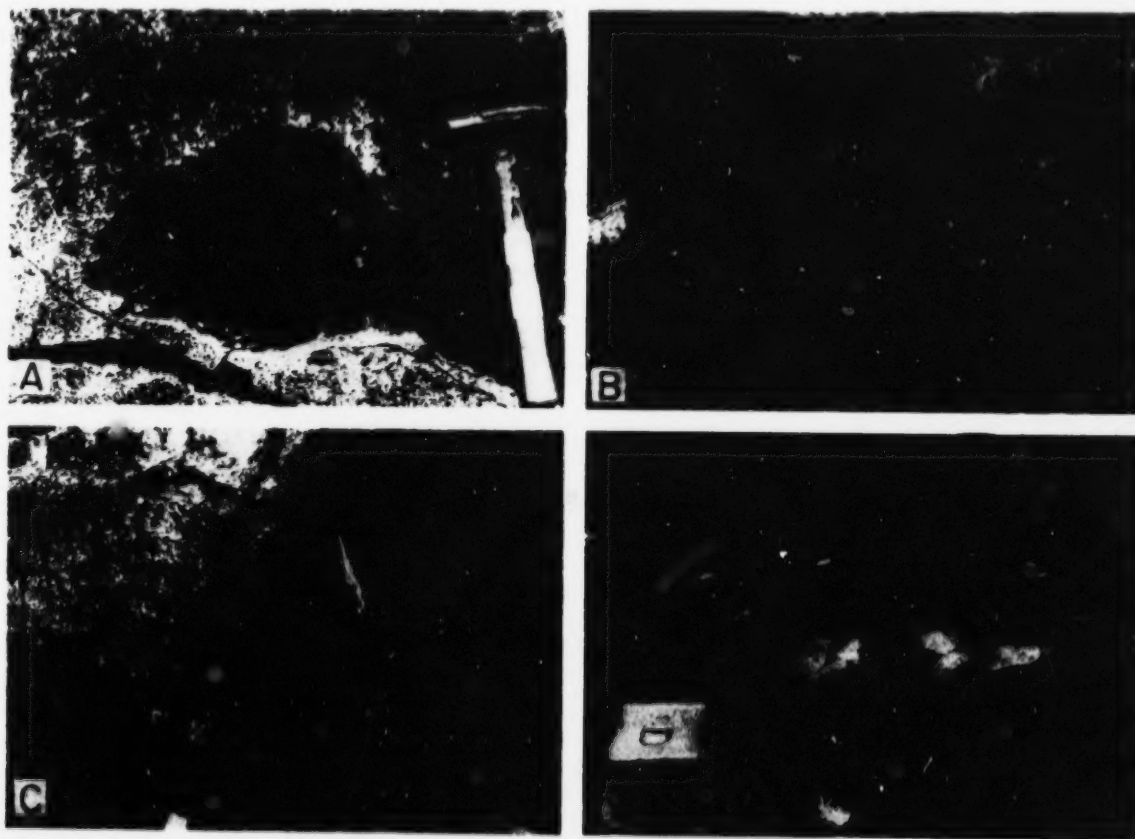


Photo 1.1. Structure and features in Archean and Proterozoic volcanic fragmental rocks. a) Aerodynamically shaped bomb in coarse tuff to lapilli-tuff, Back River Complex, Archean age, Northwest Territories. b) Bomb and bomb-sag in underlying stratified layers, Archean tuff, Rouyn-Noranda, Quebec. c) Eutaxitic structure (flattened pumice) in a Proterozoic age, partly welded, ignimbrite, Great Bear Lake, Northwest Territories. d) Large-scale stratification in lapilli-tuff and tuff-breccia, subaqueous pyroclastic flow and fall deposits, Rouyn-Noranda, Quebec.

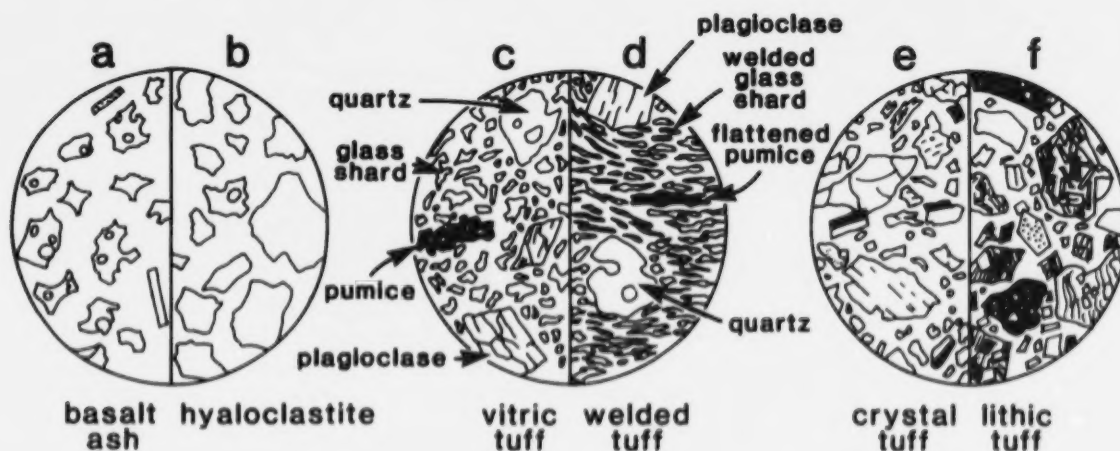


Figure 1.14. Sketch showing characteristics of various pyroclastic rocks under the microscope. Field Diameter is 2 mm. a) Sketch showing characteristic outlines of fragments in glassy basaltic ash (magmatic origin). (After Macdonald 1972). b) Sketch showing characteristic outlines of fragments in hyaloclastite (phreatomagmatic origin). (After Macdonald 1972). c) Vitric tuff from the unwelded top of an ignimbrite. The tuff consists of angular glass shards, showing typical arcuate and forked forms, bits of pumice, and crystals of quartz and feldspar. Fine dust matrix is not shown. (Modified from Macdonald 1972 and Williams et al. 1954). d) Welded tuff from base of ignimbrite is c). Constituents as in c), but pumice and glass shards are deformed and flattened. Fine dust matrix is not shown. (Modified from Williams et al. 1954). e) Crystal tuff consisting of broken crystal fragments of quartz, feldspar, and mafic minerals. Accessory rock fragments are a minor component. Fine dust matrix is not shown. (Modified from Williams et al. 1954). f) Lithic tuff containing a variety of accessory fragments, as well as broken crystal fragments and glass shards. (After Williams et al. 1954).

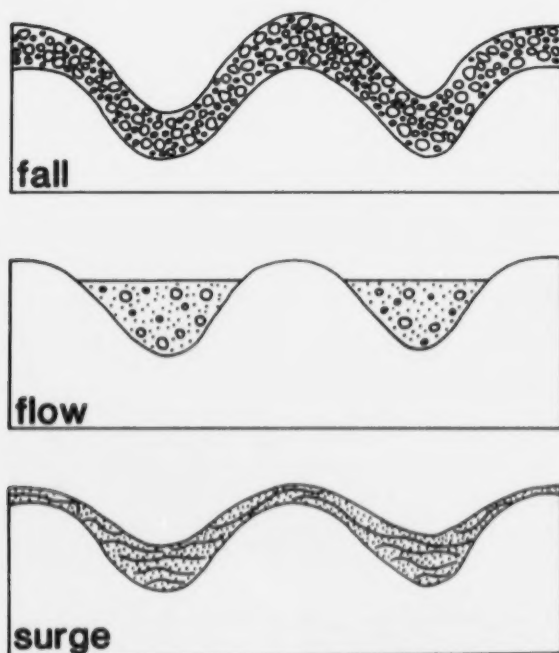


Figure 1.15. The three main types of pyroclastic deposit based on depositional mechanism, and their geometric relations with the underlying topography. (After Wright et al. 1960).

the Archean rock record, are uncommon relative to fall and flow deposits.

Characteristics of the 3 main pyroclastic types are listed in Table 1.6. Table 1.7 describes the types of pyroclastic flows found in recent volcanic terrains; Table 1.8 compares summary descriptions of the various types of pyroclastic flow and surge deposits. Figure 1.16 shows the classification scheme for pyroclastic fall deposits proposed by Wright et al. (1980). This scheme cannot be rigorously applied to Archean terrains, although areally well distributed rocks in Archean volcanic belts could be distinguished in a rough way using this scheme.

In terms of classification, genetic interpretations can best be indicated by a prefix, for example, "air-fall tuff", "laharic ash-lapilli tuff", "vent agglomerate". Purely genetic terms, such as "hyaloclastite" and "lahars" should only be used where the deposit is well described. One man's "lahar" may be another's "phreatic breccia". This confusion in terminology can only be resolved by detailed rock descriptions (see next section and Table 1.9 for suggestions on what should be included in such descriptions).

CRITERIA USED TO DISTINGUISH TYPES OF VOLCANIC FRAGMENTAL ROCKS

In terms of potential utility in mapping and exploration, it is not only necessary to be able to subdivide pyroclastic rocks into lithologic types, but it is neces-

TABLE 1.9: SOME CHARACTERISTICS OF THE 3 MAIN PYROCLASTIC DEPOSIT TYPES (AFTER WALKER 1981).**1. Pyroclastic fall deposits show:**

- (a) mantle bedding
- (b) good to moderate sorting
- (c) more or less exponential decrease in thickness and grain size with distance from vent
- (d) block impact structures

Exception - water-flushed ash may show (a) only, but gives independent evidence for water flushing (e.g. accretionary lapilli, vesicles). Fall deposits can be sufficiently hot when they accumulate to show primary welding near vent.

2. Pyroclastic flow deposits show:

- (a) ponding in depressions, with a nearly level top surface
- (b) irregular thickness variation with distance from vent
- (c) minimal sorting or internal stratification
- (d) evidence for being hot (e.g. welding, pervasive thermal colouration)

Exception - low-aspect ratio ignimbrites include a mantling layer which passes laterally into the valley-pond ignimbrite.

Note 1 - ignimbrite can be defined as a pyroclastic flow deposit made mostly from pumiceous material (pumice, shards).

Note 2 - primary mudflows (lahars) resemble pyroclastic flow deposits but lack (d).

3. Pyroclastic surge deposits show:

- (a) draping of topography
- (b) rapid and irregular or periodic thickness fluctuations
- (c) general decrease in thickness and grain size with distance from source
- (d) commonly erosional base

Two main types of pyroclastic surges occur:
A - cold, damp or wet...base surges; deposits show:

- (a) good internal stratification or cross-stratification
- (b) great grain size variations between contiguous beds
- (c) evidence for dampness (e.g. accretionary lapilli, vesicles, plastering of up-vent side of obstacles)
- (d) association with vents in low-lying or aqueous situations, or vents containing water (crater lakes)

B - hot, dry...surges of nuee ardente types; deposits show:

- (a) little or no internal stratification
- (b) good sorting, depletion in fine or lightweight particles (but these may occur in an overlying fall deposit)
- (c) evidence for being hot

Exception - very similar deposits underlying ignimbrite can be produced by sedimentation from the pyroclastic flow.

sary to go one step further and speculate on the mode of emplacement and the genesis of the rocks in question. Some criteria that can be used to subdivide pyroclastic rocks in the field are listed in Table 1.9. In Table 1.10, these criteria are tabulated in a form designed to show key characteristics of various volcanic breccias. In many instances, a single criterion may not be diagnostic, but several criteria may allow for distinction between various breccia types. What follows is a brief discussion of how the criteria listed in Table 1.9 can be applied. Examples are also provided. Some of the factors listed in Table 1.9 are the same factors used for rock classification.

Grain Size

In addition to its use in rock classification, as shown in Figure 1.11, grain size can be used to classify pyroclastic rocks as to mode of emplacement. In Figure 1.17, pyroclastic fall deposits generally have a lower $Md\phi$ (medium grain diameter), that is, the deposits are finer grained, and have a lower ϕ (deviation from median), that is, the deposits are better sorted, than pyroclastic flow deposits. $Md\phi$

and ϕ are determined in modern volcanic rocks through sieving. Naturally, this is not practical in Archean deposits. Mean grain size may be substituted (Schmid 1981) and can be measured on the outcrop. In addition, a qualitative estimate can be made on the outcrop of the size range in size of grains from the mean. Thus, with appropriate modification, Figure 1.18 can be adopted for use in Archean volcanic terrains. Fox (1977) has proposed that a measurement of the ten largest fragments in volcanic breccias can be a useful measure to trace very rapidly lateral grain size variations in pyroclastic breccias. In addition, lahars differ in grain-size distribution compared to pyroclastic flows, in this case, ignimbrites (Figure 1.18).

Fragment Type

Fragment type is also an important criterion for subdividing volcanic breccias, as it is in subdividing tuffs (see Figure 1.12). Important features to look for are pumice and glass shards. Abundant pumice and glass shards indicate that the deposit is an ignimbrite or pyroclastic flow. If the deposit is poorly sorted, if the deposit is well sorted, it is probably a fall deposit.

TABLE 1.7: TYPES OF PYROCLASTIC FLOWS (MODIFIED FROM SELF 1982a).

ESSENTIAL FRAGMENTS	ERUPTIVE MECHANISM	PYROCLASTIC FLOW	DEPOSIT
VESICULATED			
	ERUPTION COLUMN COLLAPSE	PUMICE FLOW	IGNIMBRITE, PUMICE, AND ASH DEPOSIT
		SCORIA FLOW	SCORIA AND ASH DEPOSIT
Decreasing average density of juvenile clasts			
	LAVA/DOME COLLAPSE	EXPLOSIVE-LAVA DEBRIS FLOW (NUEE ARDENTE)	BLOCK AND ASH DEPOSIT
		GRAVITATIONAL-LAVA DEBRIS FLOW (NUEE ARDENTE)	BLOCK AND ASH DEPOSIT
NON-VESICULATED			

Both pumice and shards can be observed with a hand lens (see Photo 1.1), or under the microscope (see Figure 1.14). Pumice in ignimbrites is often flattened due to post-emplacement compaction, or welding, or both, and deformation (see Photo 1.1).

Other features include the presence of lithic fragments, the proportion of lithic to other fragments, and their variation vertically or laterally, or both, in the deposit. Some phreatic breccias may consist almost entirely of lithic fragments (Photo 1.2). If crystals and crystal fragments are abundant, then the deposit may be an ignimbrite. Euhedral crystals may be more abundant in lava flows and domes than in ignimbrites. The presence, or absence of a dominant fragment type may also be important. A monolithic breccia is composed of fragments which have the same composition, mineralogy, texture, and colour. Such a breccia consisting of glass fragments composed of

basaltic material is most likely to be a strombolian or a hyaloclastite deposit (Photo 1.3). The presence of broken pillow rinds in addition would favour the latter (Photo 1.3). A heterolithic breccia, a breccia in which the fragments have a differing composition, mineralogy, texture, and colour, may be a phreatic breccia (Photo 1.2), a lahar, or a pyroclastic flow. If pumice is abundant, the latter is more likely. If there is no one dominant fragment type, the breccia is most likely to be a lahar (Fisher 1982b; Photo 1.2).

Fragment Shape

Phreatic and phreatomagmatic eruptions produce angular fragments (Photo 1.3). Rounded fragments may indicate pyroclastic flow deposits (Photo 1.2), or re-deposition. The variations in fragment shape are also

TABLE 1.8: SUMMARY DESCRIPTIONS OF TYPES OF PYROCLASTIC FLOW AND SURGE DEPOSITS (MODIFIED FROM SELF 1982a).

Deposit	Description
FLOW	
Ignimbrite Pumice and Ash	Unsorted ash deposits containing variable amounts of rounded salic pumice lapilli and blocks up to 1 m in diameter. The pumice fragments are generally reversely graded, whereas the lithic clasts show normal grading. The coarser smaller volume deposits usually form valley infills, whereas the larger volume deposits may form large ignimbrite sheets. They may show 1 or more zones of welding.
Scoria and Ash	Topographically controlled, unsorted ash deposits containing basalt to andesite vesicular lapilli and scoriaceous ropey surfaced clasts up to 1 m in diameter. In some circumstances, they may contain large non-vesicular cognate lithic clasts.
Block and Ash	Topographically controlled, unsorted ash deposit containing large, generally non-vesicular, jointed, cognate lithic blocks which can exceed 5 m in diameter. The deposits are usually reversely graded.
SURGE	
Base Surge	Stratified and laminated deposits containing juvenile vesiculated fragments ranging from pumice to non-vesiculated cognate lithic clasts, ash, and crystals with occasional accessory lithics (larger ballistic ones may show bomb sags near-vent) and deposits produced in some phreatic eruptions which are composed totally of accessory lithics. Juvenile fragments are usually <10 cm in diameter due to the high fragmentation caused by the water/magma interaction. Deposits show unidirectional bedforms. Generally, they are associated with maar volcanoes and tuff rings. When basaltic in composition, they are usually altered to palagonite.
Ground Surge	Generally <1 m thick; composed of ash, juvenile vesiculated fragments, crystals, and lithics in varying proportions depending on the parent pyroclastic flow (or constituents in the eruption column in the case of those not associated with a pyroclastic flow). Typically enriched in denser components (less well vesiculate juvenile fragments, crystals, and lithics) compared to parent flow. Again they show unidirectional bedforms.
Ash Cloud Surge	Thin, stratified ash deposits found at the top of the flow units of pyroclastic flows. They show unidirectional bedforms, pinch and swell structures and may occur as discrete separated lenses. Composed of ash sized material; proportions of components vary depending on the parent pyroclastic flow.

useful in distinguishing between pyroclastic deposits, as are shown in Figure 1.14 and Photo 1.3.

Welding

Welding is mainly present in pyroclastic flows (ignimbrites), and can occur in both subaqueous and subaerial pyroclastic flows. In ignimbrites in which welding is fully developed, three characteristic zones are present. These are dense, partial and incipient, and no welding (Smith 1960). Welding has been reported in some near-vent, pyroclastic surge deposits (Wright *et al.* 1980).

Sorting

As seen in the section on grain size and Figure 1.17, the rock names are an expression of both fragment sorting and size. Poorly sorted deposits are generally pyroclastic flows, lahars, and autoclastic and al-

loclastic breccias. Fall deposits are commonly well sorted.

Bedding/Stratification

Bedding thickness terms applicable to tuffs are listed in Table 1.11. For coarse breccias, no uniform terms exist to describe the stratification of large-scale bedding. Stratification does occur in some pyroclastic flows and lahars, and may be more prominent in the upper part of the deposit (see Photos 1.1 and 1.2).

Matrix

The nature of the matrix may vary considerably between volcanic breccias (Photo 1.3). The same factors used to describe the entire deposit also apply to the matrix, the mean of and range in grain size, fragment type, and shape and sorting. Is the deposit matrix- or fragment-supported?

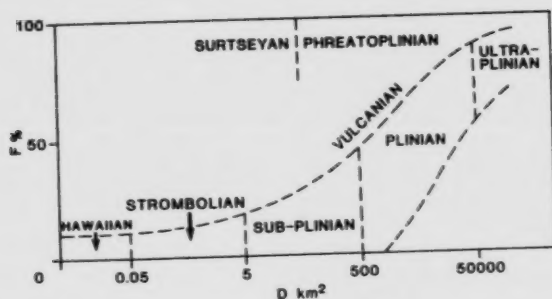


Figure 1.16. Classification scheme of pyroclastic fall deposits (after Wright et al. 1980 and Walker 1973). F is weight percentage of deposit finer than 1 mm on the axis of dispersal where it is crossed by the 0.1 T max isopach, where T = thickness. D is the area enclosed by the 0.1 T max isopach. This scheme is not readily adaptable to Archean terrains, although widespread deposits, if not reworked, are probably the result of Plinian or Ultra-Plinian eruptions.

TABLE 1.9: CRITERIA FOR SUBDIVIDING PYROCLASTIC ROCKS.

GRAIN SIZE	- mean vs. range
FRAGMENT TYPE	- glass pumice shards
	- lithic fragments
	- crystals
	- dominant fragment type (if any)

FRAGMENT SHAPE

WELDING

SORTING (may be affected by the depositional environment)

BEDDING/STRATIFICATION

MATRIX - composition, size, proportion

EXTENT OF DEPOSIT/RELATION TO ADJACENT ROCKS

TABLE 1.10: SELECTED CHARACTERISTICS OF SOME COMMON BRECCIA TYPES.

BRECCIA TYPE	FRAGMENT TYPE		FRAGMENT SHAPE		FRAGMENT		ABUNDANCE		STRATIFICATION		SORTING		WELDING	
	Monolithic	Heterolithic	Angular	Rounded	Essential only	Essential, accessory, accidental	None dominant	Pumice present	Stratified	Unstratified	Sorted	Unsorted	Welded	Unwelded
AUTOCLASTIC BRECCIAS														
FLOW BRECCIA	X		X		X → x					X	x ← X			X
CRUMBLE BRECCIA	X		X		X → x					X	x ← X			X
PYROCLASTIC BRECCIAS				X	X				X		X			X
STROMBOLIAN														
VULCANIAN BRECCIA		X	X			X				X		X		X
SUBAERIAL ASH-FLOWS	X → x		X → x		X → x			X	x ← X	X	x ← X	X	X	X
SUBAQUEOUS ASH-FLOWS	X → x		X → x		X → x			X	X	X	X → x		X	X
PHREATOMAGMATIC	X → x		X → x		X	X			X		X			X
PHREATIC BRECCIA	X	X	X			X				X		X		X
BASE-SURGE DEPOSITS	X → x		X → x		X	X			X		X			X
HYALOCLASTITES	X		X → x		X → x				X → x		X → x			X
ALLOCLASTIC BRECCIAS	X		X → x		X					X		X		X
EPICLASTIC BRECCIAS		x ← X	X → x		X → x		X → x		x ← X		x ← X			X
LAHARIC														
TALLUS BRECCIA		X	X	X		X	X → x			X		X		X

X → x - grade into

X - commonly present

x - rare to uncommon

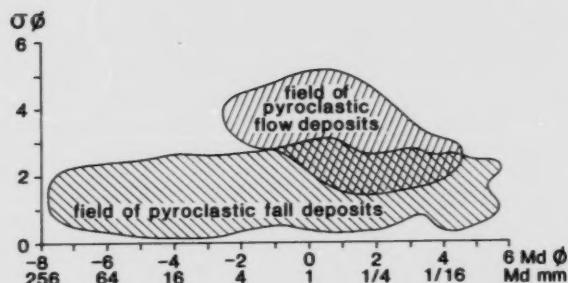


Figure 1.17. $Md\phi/\phi$ (Median grain diameter vs. deviation in grain diameter) plot showing the fields of pyroclastic fall and flow deposits (after Walker 1971, 1973; Wright et al. 1980). Note that pyroclastic flow deposits are coarse (greater $Md\phi$) and less sorted (greater ϕ) than pyroclastic fall deposits. Mean grain diameter (as measured on outcrop) and range in grain size (as measured on outcrop) can be used for Archean pyroclastic rocks, where $Md\phi/\phi$ cannot be readily measured (Schmid 1981; Fox 1977; see text for further discussion).

Facies and Extent of Deposit

Facies is important because distance from the vent will affect the degree of sorting, the size distribution, and so on. In addition, the relationship of the deposit in question to other rocks is important. For example, is the deposit part of a flow unit, or is it a flow unit in itself? (see Figures 1.3 and 1.5).

Summary

The application of these criteria is illustrated in Figure 1.19, which compares some of the more common breccia types. In Table 1.12, these criteria are used to distinguish volcanic versus epiclastic rocks.

Many pyroclastic breccias can be subdivided on the basis of origin and mode of emplacement by using the relatively straightforward criteria given above and those listed in Table 1.9. This information can then be applied to the development of a facies model for the area in question. This is elaborated on in the next section.

VOLCANIC FACIES

Introduction

One of the difficulties faced by geologists working in Archean (and other Precambrian) volcanic terrains is the interpretation of the highly varied and discontinuous outcrops of volcanic rocks present in these regions. The original constructional volcanic landform has long since been destroyed by erosion, and the normal rules applied to interpreting layered sequences of rocks have only limited application in volcanic terrains, as discussed by Trowell and Johns (Chapter 3, this volume), and Trowell (Chapter 2, this volume).

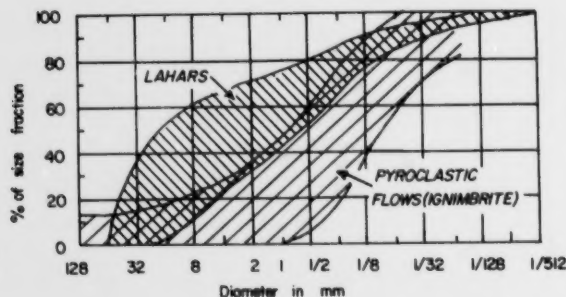


Figure 1.18. Grain-size distribution in ash-flows and lahars (after Schmincke 1974).

To cope with these problems, facies models developed for more youthful volcanic terrains, must be investigated, and then these models should be applied to Archean volcanic sequences. Facies analysis of modern and deformed volcanic rocks is still in its infancy, and facies analysis in the Archean is just beginning. In this section, the authors will review what is known about volcanic facies, and suggest how this knowledge may be applied to Archean volcanic terrains. In the final section, the authors will present some case examples of how volcanic facies have been interpreted in the Superior Province of Ontario and Quebec, and how this information can be of use in mineral exploration.

Firstly, a word of caution must be given. Facies analysis involves an examination of the lateral and vertical changes in a volcanic sequence, or a volcanic deposit. As such, it requires a regional examination of outcrops, as well as detailed outcrop study. Hence, it is not always possible to determine the volcanic facies for an area by examining only a few outcrops of limited areal extent. In addition, we must face the basic problem of dealing with deformed volcanic rocks, namely: deformation and metamorphism destroy delicate textures and structures; and analytical techniques used with unconsolidated or weakly consolidated deposits cannot be used with metamorphosed pyroclastic deposits. Despite these difficulties, knowledge of volcanic facies is critical when it comes to the interpretation of Archean volcanic terrains.

Volcanic Facies

Scale is an important consideration in regard to volcanic facies. The authors would apply different criteria in trying to understand the facies setting of a large volcanic feature, such as a shield volcano (Figure 1.20), a composite volcano (Figure 1.20), or a smaller volcanic edifice such as a cinder cone versus a particular volcanic unit or units (for example, Figures 1.3 and 1.5). We will start by examining large-scale facies variations, and proceed to deposit-scale facies variations.

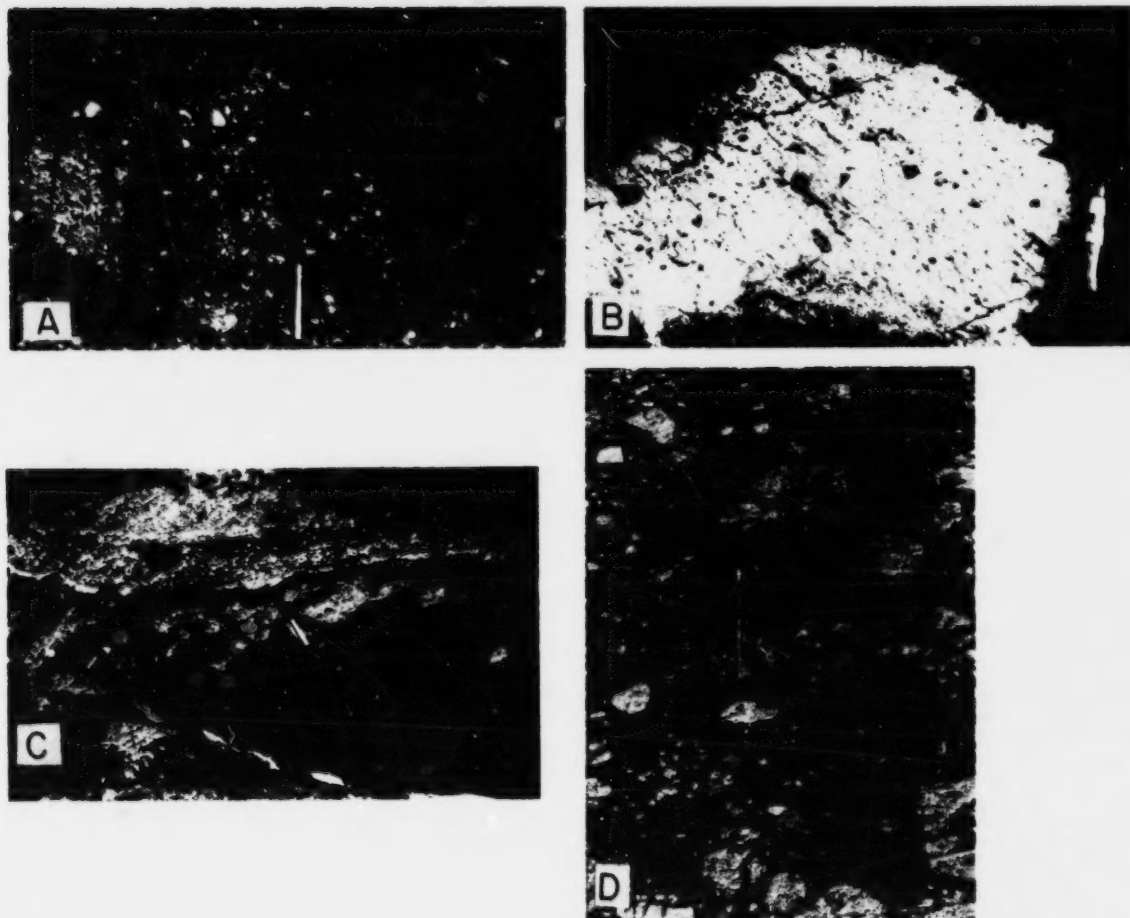


Photo 1.2. Pyroclastic breccias. a) Lahar, Back River Complex, Northwest Territories, Archean age. May be derived from flow front of a lava dome. Dark fragments are epiclastic sediments. Most fragments are lithologically similar to nearby rhyolite lava domes and flows. b) Phreatic breccia, Noranda, Quebec, Archean age. Note angular fragment size, and overall monolithic character of this outcrop. c) "Block-and-ash" flow sandwiched between an upper and lower air-fall pumice layer. Hammer is in "block-and-ash" flow. Older deposits of Mount St. Helens volcano, Washington, U.S.A. d) Subaqueous pyroclastic flow, lower massive unit is shown, Wawa, Ontario, Archean in age.

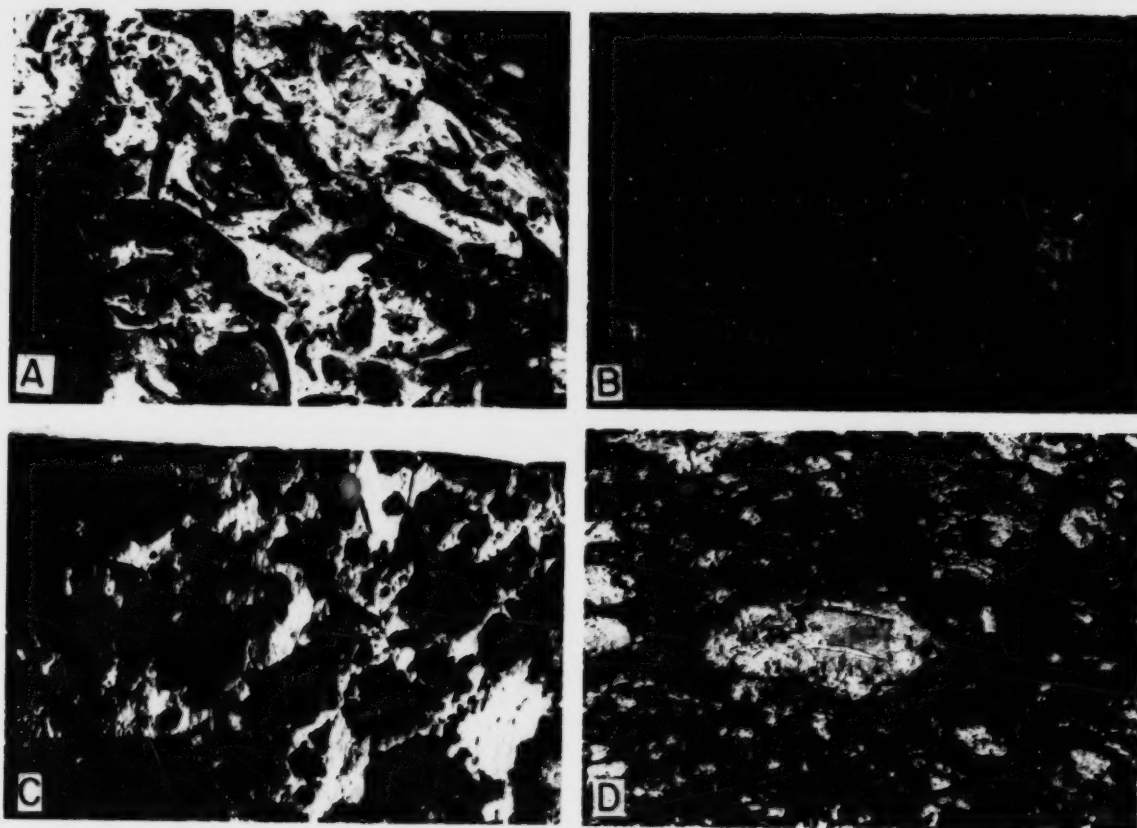


Photo 1.3. Flow breccias and hyaloclastics. a) Broken pillow fragment in hyaloclastite matrix, Rouyn-Noranda, Quebec, Archean in age. b) Disrupted rhyolite flow. Near border between massive and breccia facies as shown in Figure 1.9. Rouyn-Noranda, Quebec, Archean in age. c) Flow breccia with matrix of epiclastic, weakly laminated sediment. Back River Complex, Northwest Territories, Archean in age. d) Basal flow breccia, consisting of hyaloclastite matrix and angular fragments. Large clast by hammer is a clast from an adjacent breccia unit (top of underlying flows). Yellowknife, Northwest Territories, Archean in age.

Volcanic Facies on a Regional Scale An example of facies variation on a regional scale is illustrated in Figure 1.21, a schematic diagram of volcanic rock distribution in the Lesser Antilles volcanic arc in the Caribbean. A prevailing westerly wind direction causes considerable lithologic differences to exist between the western and the eastern basins. Air-fall and turbidity current-deposited rocks predominate in the east, debris flow and pyroclastic flow deposits dominate in the west. Similar sorts of facies variation might be expected in Archean basinal environments. Additional modern examples are described in Sigurdsson (1982).

Composite Volcano As discussed in the previous section and in Ayres (1982, 1983), an island type setting is a reasonable assumption to explain Archean late volcanic sequences. Such volcanic sequences will develop composite, central vent volcanoes, such as are shown in Figure 1.22. Volcanic

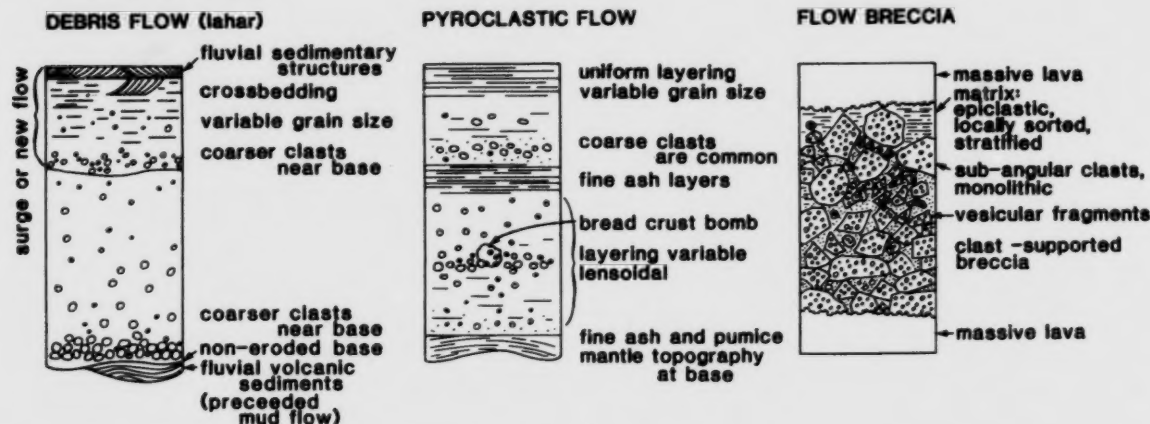
rocks of any age, or for that matter, any edifice, can be divided into 4 volcanic facies as shown in Figure 1.22:

1. central or vent facies
2. proximal facies
3. distal facies
4. epiclastic facies

The characteristics of each of these volcanic facies will vary depending on the type of volcanic edifice in question. In the Archean, the two most common are probably the composite volcano shown in Figure 1.22 and the shield volcano (Figure 1.23). The characteristics of each facies zone for a central vent volcano are listed in Table 1.13. Important features of each volcanic facies are described below.

Central or Vent Facies (0.5 to 2 km from vent) Rocks from this facies are primarily depositional in origin, and may consist of the deposit types listed in Table

PROXIMAL FACIES:



VENT FACIES:

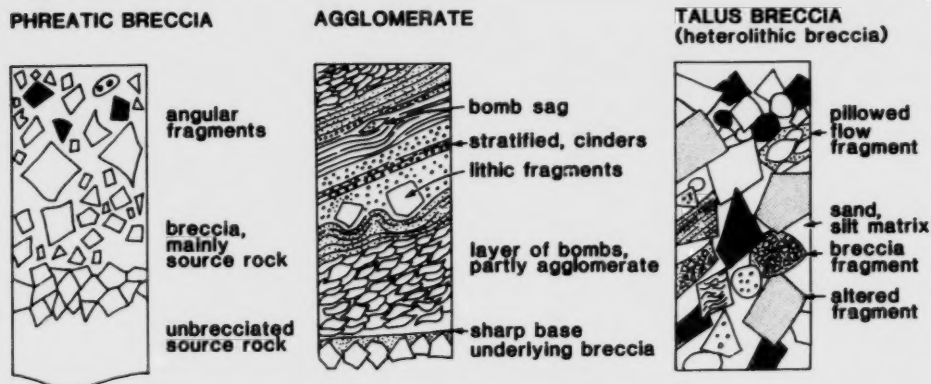


Figure 1.19. Schematic diagrams showing characteristics of some common volcanic fragmental rocks.

1.13. The important ones, with respect to massive sulphides, are dikes, sills and domes, and the crumple breccias or talus from domes. Phreatic breccias associated with the vent, or with the domes are also potential zones for mineralization. Salient features of phreatic breccias are given in Table 1.10 and Figure 1.19. The two most prevalent aspects of central or vent facies are their bewildering structural and lithologic diversity.

Proximal Facies (2 to 15 km from the vent) Rocks within this zone may be the result of primary deposition or the result of secondary transport and redeposition. The resultant deposit may be mapped as volcanic or sedimentary depending on the bias of the observer, the distance travelled, and the degree of reworking. Rocks from this facies which are depositional in origin are domes and flows with their attendant breccias, air-fall tephra, pyroclastic flow deposits, and subaqueous pyroclastic flow deposits. Redeposited rocks include debris flows (lahars), turbidites, and subaqueous pyroclastic flows. Debris

avalanche and other large-scale slump deposits may also be expected. Subaqueous pyroclastic flows, and lava flows and domes and their attendant breccias have the greatest mineral potential.

Distal Facies (5 to 15 km from the vent) Distal facies rocks can often be delineated by their greater lateral continuity. As in the proximal facies, these rocks may be the result of deposition, or, erosion and redeposition. Again, they may be mapped as volcanic or sedimentary depending on transport distance and bias. Distal facies rocks tend to be finer grained, better sorted, and more distinctly bedded than rocks found in the proximal facies.

Epiclastic Facies (0.5 to 15 km from vent) Epiclastic sediments also form in an active volcanic environment, and are intercalated with the volcanic deposits. These rocks include sheetwash fans related to flash-floods in rapidly eroding volcanic terrains; perched ponds, volcanic moats, and other lacustrine deposits, and talus and landslide deposits. As such, they can be classified as a separate facies. Their metallogenic

TABLE 1.11: BEDDING THICKNESS TERMS.

Thinly laminated	<0.3 cm
Thickly laminated	0.3 to 1 cm
Very thinly bedded	1 to 3 cm
Thinly bedded	3 to 10 cm
Medium bedded	10 to 30 cm
Thickly bedded	30 to 100 cm (1 m)
Very thickly bedded	1 m to 3 m
Extremely thickly bedded	>3 m

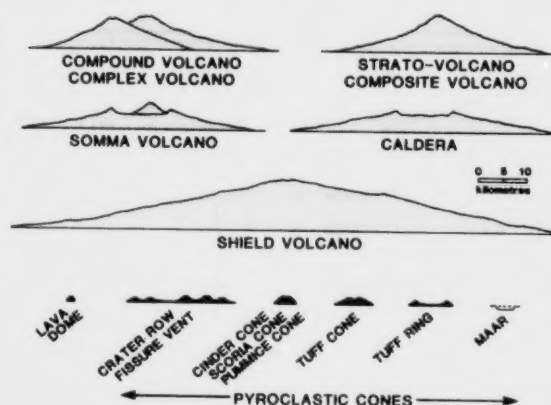


Figure 1.20. Types of volcanoes. Schematic profiles are vertically exaggerated by 2 to 1 (shaded) and 4 to 1 (dark). Relative sizes are only approximate. (After Simkin et al. 1981).

TABLE 1.12: FIELD CRITERIA USED IN THE GREENSCHIST FACIES, TO DISTINGUISH BETWEEN FELSIC METATUFF, PORPHYRITIC FELSIC FLOWS, AND POORLY BEDDED, MUSCOVITE-BEARING METAGREYWACKE. MOST OF THESE CRITERIA ARE MORE EASILY RECOGNIZED ON WEATHERED SURFACES THAN ON FRESH SURFACES (AFTER AYRES 1969).

FELSIC METATUFF

1. Abundant sand-size, lenticular, felsic fragments
2. Rare sand-size, lenticular, mafic fragments
3. Abundant angular, sand-size plagioclase
4. Rare sand-size quartz
5. Rare felsic metavolcanic lapilli
6. Abundant, wispy, very fine grained, quartz - plagioclase - white mica matrix

PORPHYRITIC FELSIC FLOWS

1. Sand-size rock fragments absent
2. Rare metavolcanic lapilli
3. Subhedral to euhedral, locally oriented, fine- to medium-grained, plagioclase phenocrysts
4. Rare fine- to medium-grained, quartz phenocrysts
5. Abundant very fine grained, locally aphanitic, quartz-plagioclase-white mica groundmass

MUSCOVITE-BEARING METAGREYWACKE

1. Rare visible, sand-size rock fragments
2. Abundant sand-size quartz
3. Abundant angular to rounded, sand-size plagioclase
4. Sand-size quartz and plagioclase appear to form an intact to slightly disrupted framework; visible matrix is rare
5. Rare quartz, metachert, and felsic and mafic metavolcanic pebbles

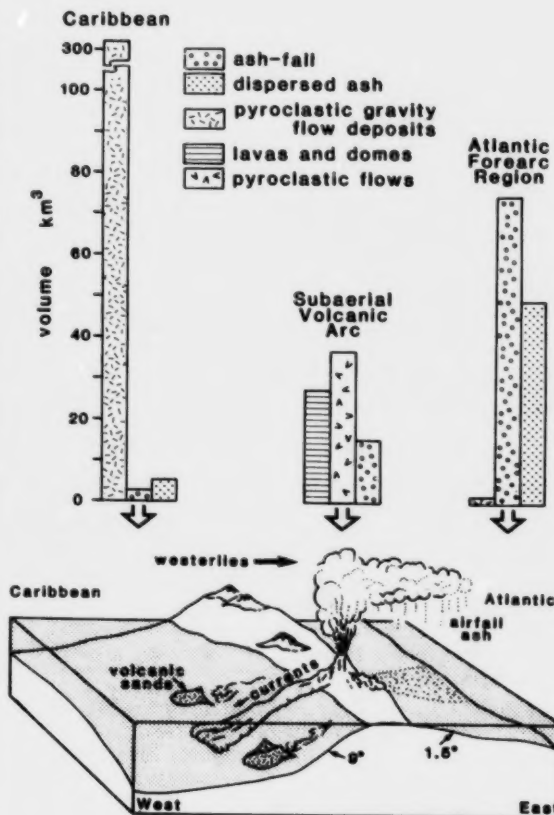


Figure 1.21. Pyroclastic rock distribution in the western and the eastern Caribbean. (Adapted from Sigurdsson et al. 1980).

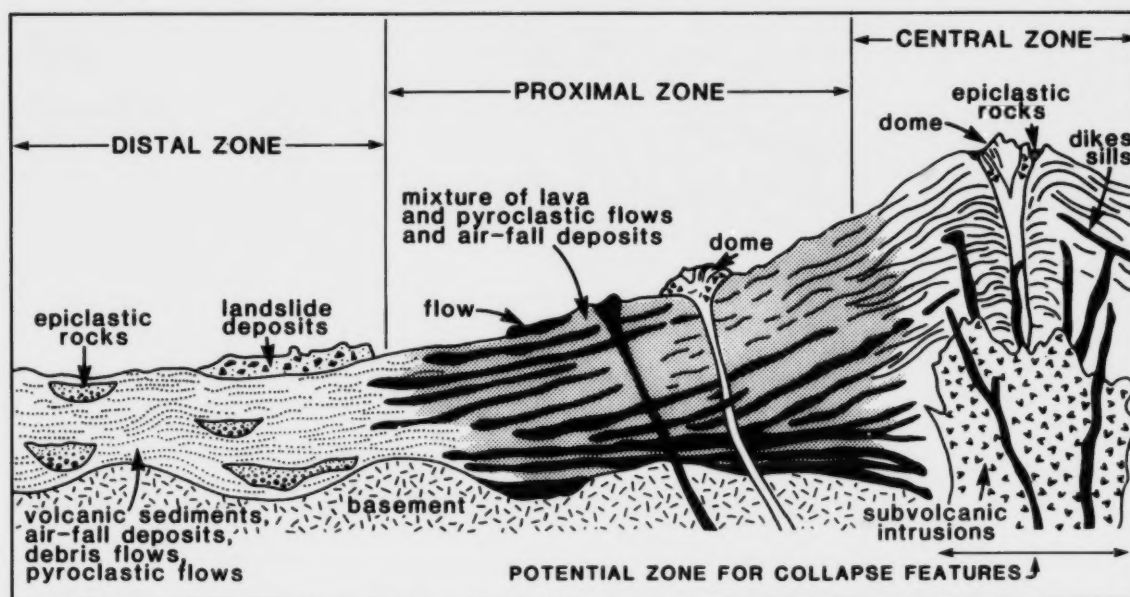


Figure 1.22. Principal facies variation in volcanic rocks related to a large central vent composite volcano. Central zone is also known as the vent facies. Epiclastic facies can occur in all three zones. Products of each zone/facies are listed in Table 1.13. (Modified from Williams and McBirney 1979).

significance may be to serve as a caprock or an aquifer for hydrothermal systems, and thus may be closely associated with ore in some instances.

Mafic Shield Volcano Shield volcanoes are probably the best analogy for the large, mafic volcanic piles that constitute the bulk of the volcanic material present in Archean "greenstone belts". There is probably not a great deal of difference between the volcanic facies present in a subaerial (Figure 1.23a) and a submarine shield (Figure 1.23b). Important features of each facies are described below.

Central or Vent Facies (0.5 to 2 km from the Vent) Rocks from this facies are primarily depositional in origin, and may consist of the deposit types listed in Table 1.14. The important ones with respect to mineralization are found in the vent complex, an area of collapse features, talus cones, minor subaerial and submarine shields. Phreatic breccias and phreatomagmatic deposits can also be expected in this facies.

Proximal Facies (2 to 15 km from the vent) Rocks within this zone are mainly the result of primary deposition. In the Archean, subaerial lavas would be for the most part eroded, so pillow lavas will be the main rock type in this setting. Massive lavas will be abundant near the vent, with the pillowed lavas increasing in abundance as distance from the vent increases. Flow thickness will generally decrease away from the vent. Subaqueous debris flows and tuffs will also be present. If another sediment source region is present adjacent to the shield volcano,

wackes and other epiclastic rocks will also occur in the upper part of the volcanic sequence. Shear zones, possibly the remnant of syn-volcanic faults, may also form in this zone.

Distal Facies (5 to 15 km from the vent) As in the proximal facies, pillow lavas will be the dominant rock type, but massive lava will be uncommon, and both tube-fed and isolated pillow types will be present. Flow breccia and pillow breccia will also be more abundant. Tuffaceous material will be more common, and landslide and debris avalanche deposits may also be present. Wackes and other epiclastic rocks can be expected to be interdigitated with the distal flow rocks and breccias.

Volcanic Facies on a Deposit Scale Volcanic facies regimes can also be recognized in deposits from a single eruption, either as lateral or vertical scale variations or both. As shown in Figure 1.24, the facies variations are the result of a change in transport mechanism and depositional mechanism with increasing distance from the vent. Figure 1.24 applies to both pyroclastic and epiclastic deposits. Fisher (1982a, 1982b) and Fisher and Schmincke (1984) illustrated in greater detail, the nature of the flow mechanisms involved. Deposit scale variations can also occur in both mafic and felsic composition rocks, as outlined below.

Felsic and Intermediate Pyroclastic Flows An example of facies variation in a deposit from a single eruptive event is shown in Figure 1.3, which depicts a subaerial pyroclastic flow. The left-hand side of

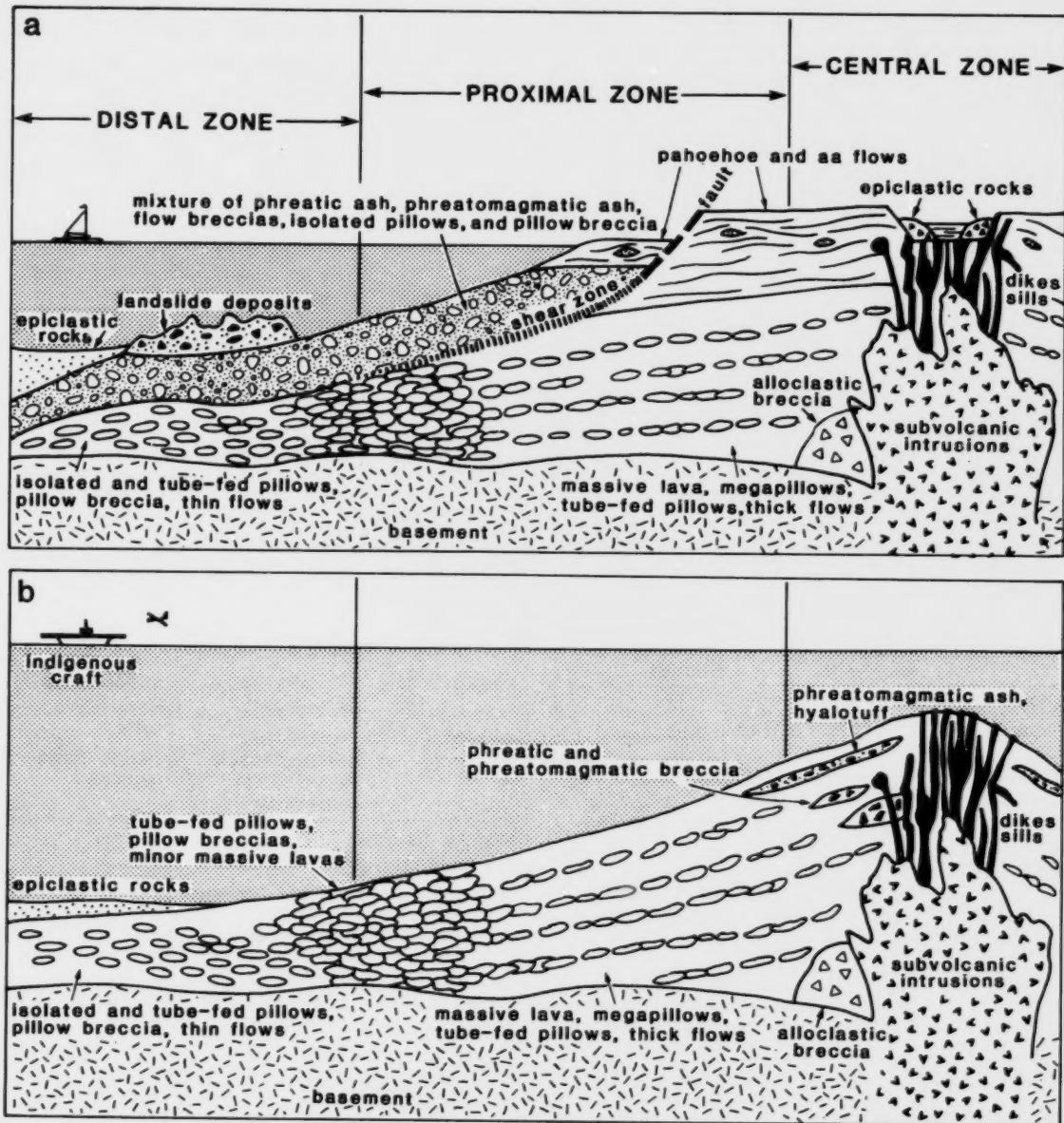


Figure 1.23. Principal facies variation in volcanic rocks related to a large shield volcano. Central zone is also known as the vent facies. Upper half shows a subaerial and a submarine volcano, lower half shows a subaerial and a submarine volcano. Model is based on knowledge of Hawaiian-type shield volcanoes. Note, vertical exaggeration 2X, horizontal shortening, 5X. Products of each zone are listed in Table 1.14. Compare with Figure 1.22.

TABLE 1.13: PRODUCTS ASSOCIATED WITH THE 4 MAIN VOLCANIC FACIES OF A CENTRAL VENT, COMPOSITE VOLCANO, AS SHOWN IN FIGURE 1.22. (ADAPTED FROM WILLIAMS AND MCBIRNEY 1979).

CENTRAL OR VENT FACIES

(within 0.5 to 2 km vent)

- Depositional - dikes, sills, and domes
 - co-ignimbrite lag deposits
 - phreatomagmatic deposits
 - talus breccia, megabreccia

PROXIMAL FACIES

(up to 2 to 15 km from vent)

- Depositional - air-fall deposits (tuffs)
 - pyroclastic flows
 - subaqueous pyroclastic flows
 - lava flows and domes

- Redeposited Recognizable as - lahars
 volcanic - pyroclastic flows
 - tuffs
 Recognizable as - debris flows
 volcanic - arenites
 sediments - wackes

DISTAL FACIES

(more than 5 to 15 km from vent)

- Depositional - air-fall deposits (tuffs)
 - pyroclastic flows
 - subaqueous pyroclastic flows
 - lava flows

- Redeposited - Recognizable - lahars
 as volcanic - pyroclastic flows
 - tuffs
 - Recognizable - debris flows
 as volcanic - arenites
 sediments - wackes
 - siltstones

EPICLASTIC FACIES

- Redeposited - talus
 - debris flows
 sediments - in crater lakes (active, extinct)
 - perched ponds
 - alluvial fans

TABLE 1.14: PRODUCTS ASSOCIATED WITH THE MAIN VOLCANIC FACIES OF A MAFIC SHIELD VOLCANO, AS SHOWN IN FIGURE 1.23.

CENTRAL OR VENT FACIES

(within 0.5 to 2 km of vent)

- Depositional - dikes, sills, subvolcanic intrusions
 - hydrothermal alteration related to subvolcanic intrusions
 - alloclastic breccias
 - phreatomagmatic and phreatic deposits
 - talus breccia, fault breccia, caldera fill
 - thick flows in pit craters (subaerial only)

PROXIMAL FACIES

(up to 2 to 15 km from vent)

- Depositional - air-fall deposits (tuffs)
 - thick-bedded lava flows, mainly massive lava, minor pillow lava and pillow breccias, tube-fed pillows

- Redeposited - Recognizable - subaqueous
 as volcanic debris flows
 - tuffs
 - Recognizable - debris flows
 as volcanic - wackes
 sediments

DISTAL FACIES

(more than 5 to 15 km from vent)

- Redeposited - air-fall deposits (tuffs)
 - thin-bedded tube-fed pillowed lava and pillow breccia, isolated pillows
 - landslide and debris avalanche deposits

- Recognizable as - subaqueous
 volcanic debris flows
 - tuffs
 - Recognizable - debris flows
 as sedimentary - wackes
 - siltstones and mudstones

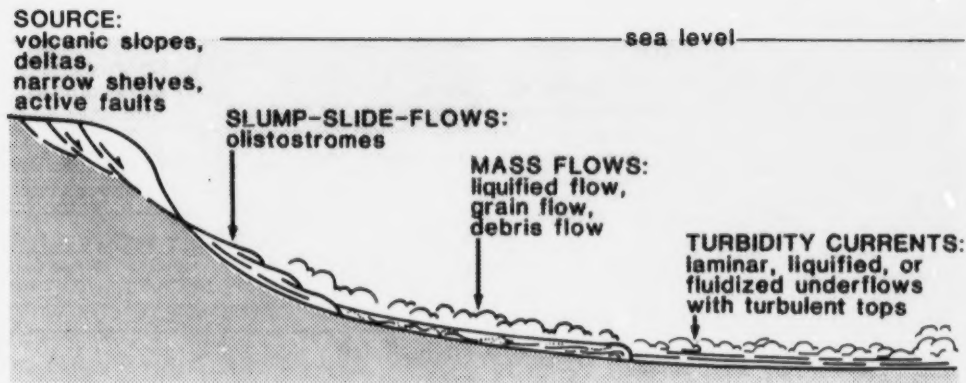


Figure 1.24. Conditions of initiation and types of subaqueous transport. Range of subaqueous transport influences the type of deposits found in volcanic facies regime. Scale of figure ranges from 10s of m to 100s of km. (After Fisher 1982b).

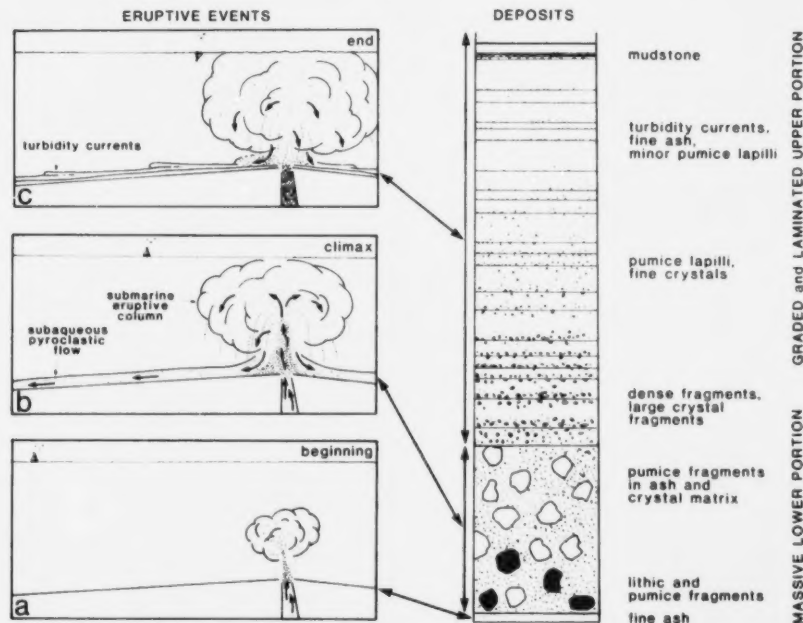


Figure 1.25. Schematic drawings of a submarine eruption producing subaqueous pyroclastic flows, and subsequent appearance of the deposits of such an eruption. A. Beginning of eruption. Vesiculating magma is erupted into sea water. Some fine ash may be deposited near the vent. B. Climax of eruption. Submarine column carries much debris high into suspension. Sorting splits the debris into various fractions. Buoyant pumice floats; dense fragments, large crystals, and compact pumice lapilli settle around the vent, and are transported laterally in a subaqueous pyroclastic flow. Most ash remains in suspension. C. End of eruption. Steady pyroclastic flow ceases as amount of erupted material decreases and is replaced by turbidity current flow. Later turbidity currents contain finer and less dense has settled from suspension. As shown in the right-hand side of the figure, an important characteristic of subaqueous pyroclastic deposits are their doubly graded nature. Each bed is graded, and the beds at the base of the sequence contain coarser and denser ash than the beds at the top of the sequence. (Modified from Fiske and Matsuda 1964 and Fiske 1969).

PROXIMAL

DISTAL

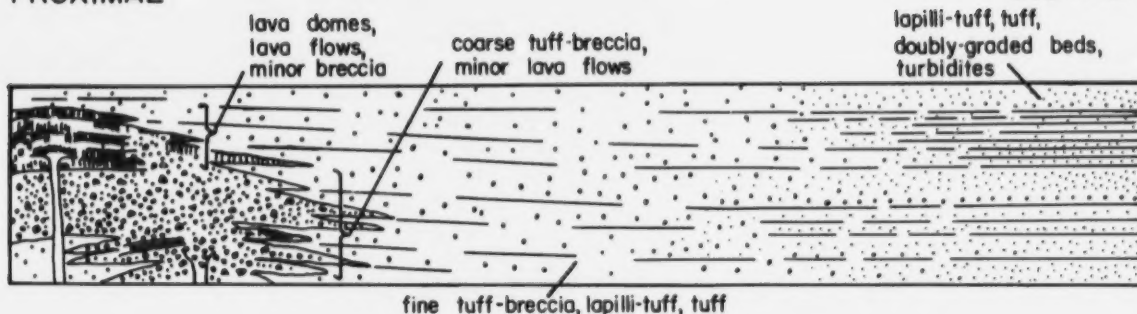


Figure 1.26. Lateral facies variation in subaqueous pyroclastic flows. (Based on data from Fiske 1963, Fiske and Matsuda 1964).

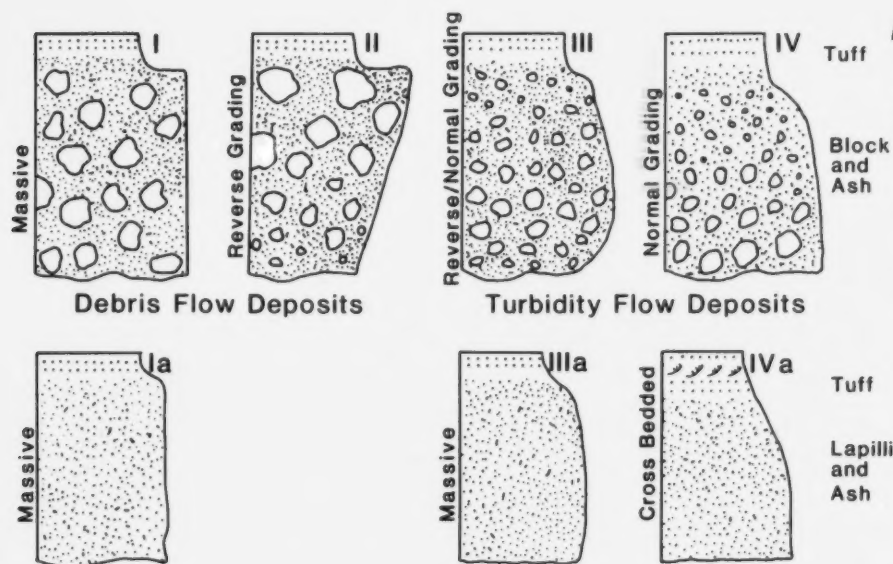


Figure 1.27. Structure sequences of subaqueous pyroclastic flows. See text for details. (Modified from Tasse *et al.* 1978 and Dimroth and Rocheleau 1979).

Figure 1.3 shows the model developed by Sparks *et al.* (1973) for pyroclastic flows, and the right-hand side shows a section through the central part of the deposit.

More relevant to the Archean would be a model for subaqueous pyroclastic flows, such as the one developed by Fiske and Matsuda (1964). Key features of their model are illustrated in Figure 1.25, and include a massive lower part, which fines upward in terms of non-vesicular material, and an upper laminated part, which also fines upward. Reverse grading is common in some beds due to flotation of pumice (vesicular). The two units are often referred to as a doubly graded sequence, and they have been recognized in the Archean, for example, in the Skead Group as discussed in the next section. With increasing distance from the vent, bedding becomes more

prominent, and the upper laminated deposits are more commonly emplaced as turbidity currents (Figures 1.25, 1.26). Smaller eruptive events would mainly form graded, laminated deposits in the proximal environment. In a larger eruption, graded, laminated deposits would occur farther from the vent (that is, in a more distal environment).

As discussed by Dimroth and Rocheleau (1979) and Tassé *et al.* (1978), subaqueous pyroclastic flows commonly show diagnostic structure sequences (Figure 1.27; Walker 1976). Walker (1976) interpreted sequence I (disorganized bed) as debris flow deposits, and structures III and IV (normal graded bedding) as turbidites. Reversed graded bedding is the result of shearing during deposition. Proximal-distal changes noted by Tassé *et al.* (1978) are as follows:

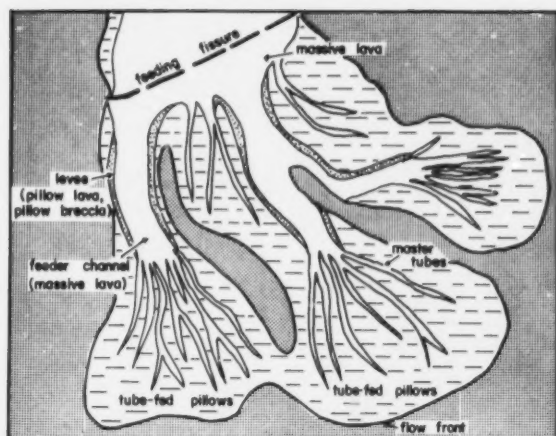


Figure 1.28. Facies model for subaqueous mafic flows on the flank of a shield volcano, showing proximal massive facies and distal pillowed facies. Cross sections of this facies regime are shown in Figure 1.5. (Modified from Dimroth and Rocheleau 1979).

1. Bed thickness and grain size decrease away from the source.
2. The number of disorganized beds and beds with reverse grading decreases away from the source.
3. The number of beds with normal grading increases away from the source.
4. The thickness of stratified upper divisions of beds increases away from the source.

Mafic Flows A facies model for subaqueous mafic flows on the flank of shield volcano is shown in Figure 1.28 and is based on the work of Dimroth *et al.* (1978, 1979) and Dimroth and Rocheleau (1979). Near the vent, high flow rates result in the extrusion of mainly massive lava. As distance from the vent increases, large channel systems develop, and are akin to tube-fed subaerial flows (Swanson 1973). With a further increase in distance from the vent, the lava channel forms tube-fed pillow lavas. Cross sections of such a flow system are shown in Figure 1.5.

Environment Indicators One important aspect in the assignment of volcanic facies, and in the application of the appropriate facies model is the determination of the depositional environment, that is, subaerial or subaqueous, and if the latter, what water depth is involved. If this knowledge is available, constraints can be placed not only on the type of deposits to be expected in a particular facies, but also on the eruptive processes that may have produced those deposits. Figure 1.29 is an illustration of the various environmental indicators that can be used in the field, and the constraints they place on the setting of volcanic activity.

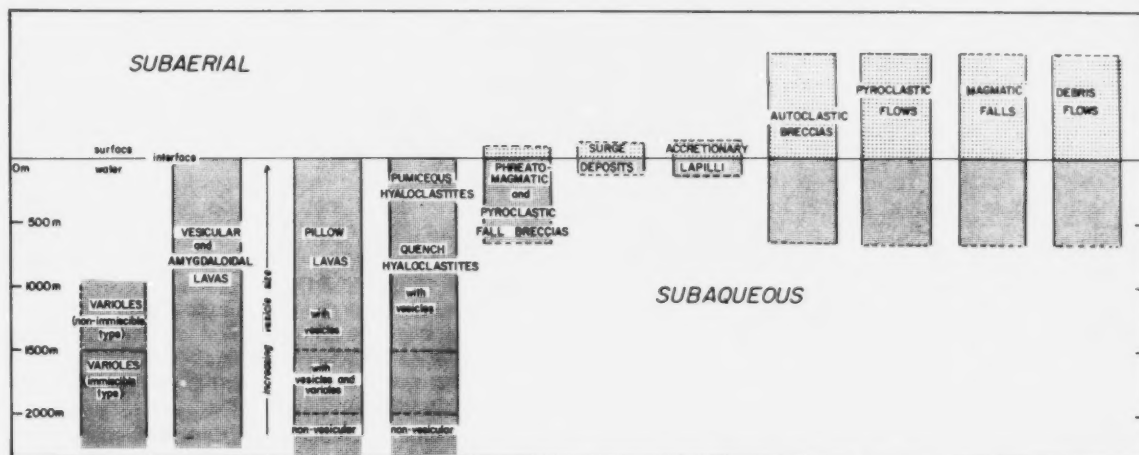


Figure 1.29. Environment of formation of volcanic breccias and specific lava flow features (water depth figures only approximate).

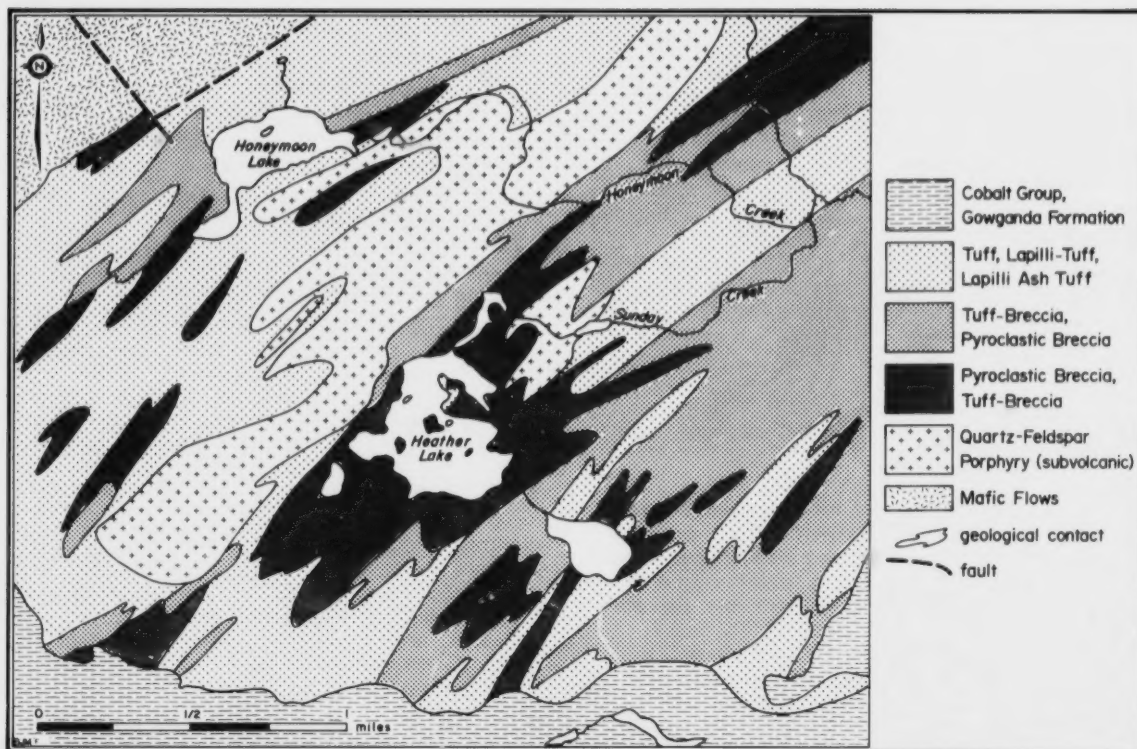


Figure 1.30. Distribution of the pyroclastic rocks of the Skead Group in southern Bryce and Tudhope Townships (from Figure 13 in Johns 1983). See Figure 1.31 for distribution of volcanic facies.

Summary The various models that exist for volcanic regimes that seem most applicable, or have been previously applied to Archean volcanic rocks have been outlined in this section. Volcanic facies analysis in Archean terrains is still in its infancy, and improvements will undoubtedly be made on the models presented here. In the next section, the authors illustrate the use of volcanic facies information in mapping Archean sequences, and its role in mineral exploration.

CASE STUDIES

MAPPING OF PYROCLASTIC SEQUENCES AND IDENTIFICATION OF VOLCANIC FACIES

The next two examples illustrate how the principles outlined in the previous sections can be applied to actual rock sequences in the Archean of the Superior Province. In both examples, one of the authors (G.W. Johns) has mapped a pyroclastic accumulation at a scale of 1 inch to 1/4 mile with the Ontario Geological Survey, and subsequently has assigned the pyroclastic rocks to a volcanic facies setting.

Example 1 - Skead Group, Abitibi Subprovince

The Skead Group pyroclastic rocks lie within the Abitibi Subprovince in the vicinity of Elk Lake (Bryce

Township) and have been described by Johns (1983). Figure 1.30 is a map of the generalized distribution of the pyroclastic rocks. Figure 1.31 is an interpretation of the facies distribution of the rocks shown in Figure 1.30. Both figures are based on information collected in 1980 (Johns *et al.* 1981). The geological units shown in Figure 1.30 are based on the major pyroclastic type present in each unit. Finer or coarser material may also be present in association with the main rock type.

All the pyroclastic rocks shown within the facies boundaries (Figure 1.31) are genetically related, as many outcrops contain multiple pyroclastic rock types gradational into one another. The coarser, unsorted pyroclastic rocks grade into finer unsorted pyroclastic rocks. Sharp contacts have been observed and finer grained beds pinch out along strike.

The greatest abundance of coarse pyroclastic rocks is in the vicinity of Heather Lake (Figure 1.30) where a 700 m thick amoeboid-shaped deposit composed of predominantly pyroclastic breccia is 2500 m long and grades laterally and vertically into predominantly tuff-breccia. These pyroclastic breccias are poorly to moderately sorted and include both clast- and matrix-supported parts. Mafic and intermediate to felsic clasts are round to angular and many have bleached reaction rims. Essential clasts include

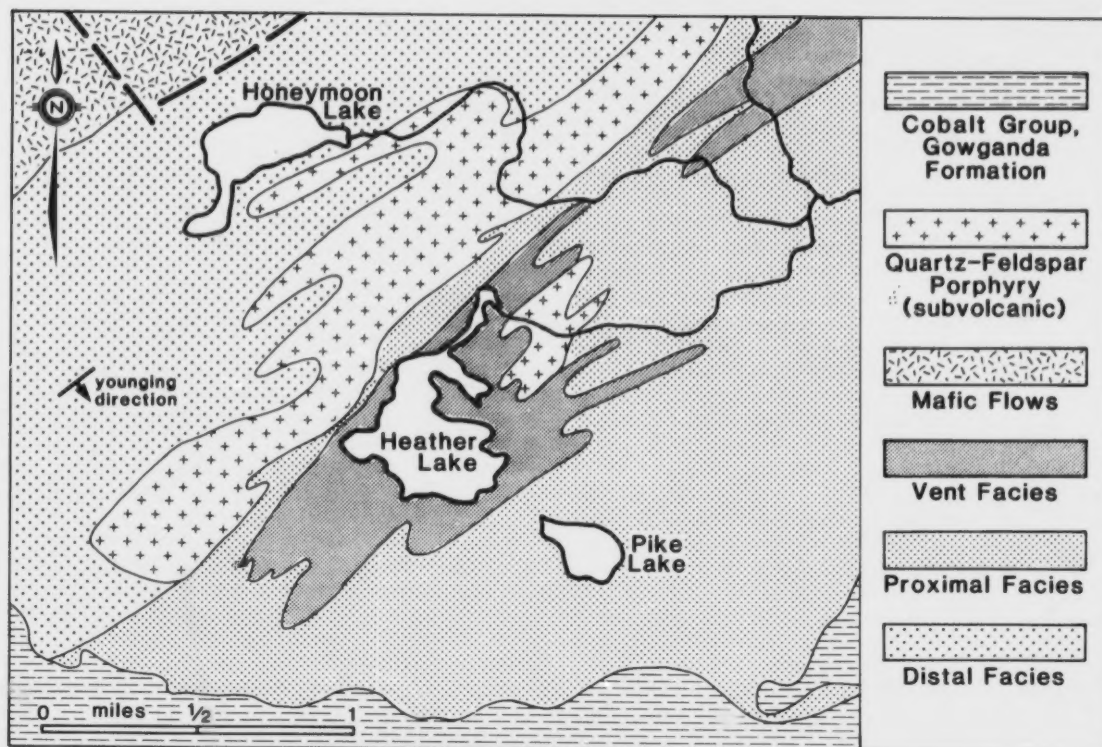


Figure 1.31. Distribution of volcanic facies of the pyroclastic rocks of the Skead Group in southern Bryce and Tudhope Townships.

clasts consisting of quartz-feldspar porphyry, similar to the body stratigraphically below the breccias (Figure 1.30). Accessory material includes lithic clasts of tuff, lapilli-tuff, and lapilli-tuff-breccia. The matrix composed of lithic and crystal ash and lapilli, is generally more mafic in composition than the clasts.

In the immediate vicinity of Heather Lake, the pyroclastic breccia is very coarse, angular, very poorly sorted, unbedded, and heterolithic. Away from Heather Lake, the pyroclastic breccia deposit becomes finer, contains more subangular fragments, and forms thick indistinct beds. This assemblage also contains fine epiclastic material gradational into the pyroclastic breccia. Sharp contacts between the individual pyroclastic deposits are not common.

These very coarse, chaotic pyroclastic breccias are vent facies deposits (Figure 1.31). The lack of stratification is the result of deposition from phreatic eruptions and rapid, direct deposition. The heat source giving rise to these phreatic explosions was the quartz-feldspar porphyry stratigraphically below the deposit.

Tuff-breccia, composed of a massive, thick-bedded, chaotic assemblage laterally interdigitates with and immediately overlies the pyroclastic breccia. These rocks are poorly sorted, matrix-supported, and

contain subangular to subround clasts of feldspar-phryic tuff, hornblende porphyry, pumice, vesiculated mafic material, and ribbed mafic bombs. The matrix is composed of euhedral and broken crystal ash and lithic ash and lapilli.

These deposits are composed of both essential and accessory clasts. These rocks were deposited in the near proximal volcanic environment (Figure 1.31). The massive poorly to indistinct bedding and the gradation with other pyroclastic deposits was due to rapid, continuous deposition from phreatic magmatic eruption of varying magnitude. These deposits were emplaced as subaqueous debris flows as is shown in Figure 1.25b.

Lapilli-tuff is interbedded or is in gradational contact with the coarser pyroclastic rocks. Lithic clasts are rounded to subrounded feldspar porphyry, pumice, and mafic volcanic material. The matrix is composed of ash-sized feldspar and pyroxene crystals, lithic fragments, and amygdaloidal and globular altered glass. Lapilli-ash tuff, a chaotic assemblage of lapilli, ash, and minor blocks is interbedded with tuff, lapilli-tuff, and tuff-breccia.

These deposits, composed of essential and accessory clasts, were emplaced in a proximal environment by phreatomagmatic eruptions. Deposition was rapid and continuous as subaqueous debris flows.

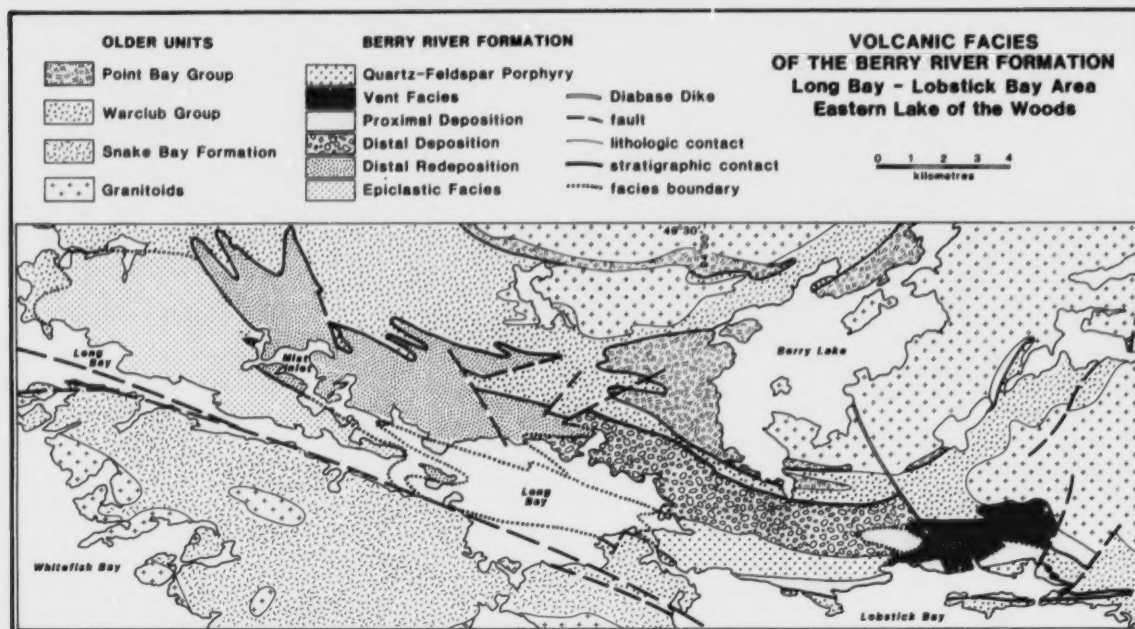


Figure 1.32. Volcanic facies of the Berry River formation, eastern Lake of the Woods. See text for further details.

The irregularly shaped quartz-feldspar porphyry intrusion stratigraphically below the proximal facies deposits (Figure 1.31) has sharp contacts. Metamorphosed fragments of the pyroclastic host rock are found within the porphyry as incorporated blocks which have indistinct boundaries. This intrusion is envisaged to be, in part, a high-level magma chamber.

The majority of the finer pyroclastic material northwest of Heather Lake (Figure 1.30) occurs in the stratigraphically lower part of the sequence. These rocks are generally fine grained and have sharper contacts than in the southeastern part of the area. These rocks are interpreted to occur in the distal facies (Figure 1.31). They were emplaced as pyroclastic flows similar to those described by Fiske (1963). Dimroth and Rocheleau (1979) described similar rocks from the Noranda-Rouyn area of Quebec. Under their classification, the distal facies units are turbidity flow deposits (see Figure 1.27). The source area for these deposits is not known.

Figure 1.26 is an idealized cross section of the Ohanapcosh Formation in Washington, U.S.A. (Fiske 1963), and shows some similarity with the distribution of the pyroclastic rocks as seen in Figure 1.30. The general model for the pyroclastic rocks in the vent or proximal facies (Figure 1.31) may be similar to that proposed by Fiske (1963) for the Ohanapcosh Formation.

Example 2 - Berry River formation, Wabigoon Subprovince

The Skead Group pyroclastic rocks discussed above are relatively undeformed, and hence are relatively easy to interpret compared to most Archean examples. It is still possible, however, to assign facies settings to more severely deformed pyroclastic rocks by cautiously applying similar principles. The facies contacts may not be as precisely located, but working hypotheses can be developed.

Mapping of the deformed metavolcanic rocks in the eastern part of the Lake of the Woods has divided the pyroclastic rocks of the Berry River formation into volcanic facies (Figure 1.32). The Berry River formation is a 2713.9 Ma year old (Davis and Edwards 1982) intermediate to felsic metavolcanic complex consisting of quartz-feldspar porphyry and pyroclastic rocks with minor interbedded sedimentary rocks. The stratigraphic setting of the Berry River formation within the western Wabigoon Subprovince is described by Trowell and Johns (Chapter 3, this volume). In brief, it is a predominantly pyroclastic complex within the Warclub group of metasedimentary and metavolcanic rocks.

Two ages or events of intermediate to felsic pyroclastic volcanism appear to have built the Berry River formation. The distal depositional and the distal redeposition facies are the products of the older event. The quartz-feldspar porphyry, vent facies, and proximal deposition facies are the result of the younger event.

Between the northeastern shore of Long Bay and the diabase dike (Figure 1.32), the pyroclastic rocks of the distal deposition facies overlie the Warclub group with a slight unconformity. These rocks vary from pyroclastic breccias to tuffs. Tuff and lapilli-ash tuff predominate, with tuff-breccia the next dominant rock type, and pyroclastic breccia the least abundant. Clasts are felsic to intermediate in composition, are equigranular, subrounded to subangular, and matrix-supported. Individual units are distinct and range from very thickly to very thinly bedded. Many of the bedded units exhibit double-grading similar to those shown on the right-hand side of Figure 1.25. These beds were deposited by subaqueous debris flows, resulting from a volcanic process similar to the one proposed by Fiske and Matsuda (1964) and shown on the left-hand side of Figure 1.25. Fine-grained, thin-bedded metasediments are found interbedded with the pyroclastic rocks. The source of these pyroclastic rocks was to the east, perhaps in the area where the Kishquabik Lake Stock is presently located.

Associated with these distal deposited pyroclastic rocks are the laterally interdigitated rocks classed as distal redeposited. These overlie and are infolded with the Warclub group. Generally, these rocks are finer than the distal deposited pyroclastic rocks, and tuff and lapilli-ash tuff predominate. Doubly graded beds are not common, but normal grading does occur. In the vicinity of Mist Inlet, wacke interbedded on an outcrop scale with redeposited pyroclastic rocks is common. The clasts within the pyroclastic rocks are subrounded to subangular and heterolithic. Clasts of wacke are found within some of the pyroclastic beds. Scouring of the underlying beds has also been noted. This facies consists of reworked and redeposited pyroclasts from the aforementioned proximal deposition facies.

The younger sequence of pyroclastic rocks of the Berry River formation overlie the two previous facies (Figure 1.32). If there is a hiatus present, the length of time involved is not known.

The vent facies rocks found southeast of Berry Lake consist primarily of an ovoid quartz-feldspar porphyry body containing xenoliths and large rafts of pyroclastic material. Parts of the porphyry are massive, but others are subtly clastic or brecciated. The porphyry has a distinctive lithologic type with phenocrysts of rounded white and blue quartz and smaller euhedral sericitized feldspar in a very fine grained to crystalline matrix. This porphyry may in part be a high-level subvolcanic intrusion, and in part an extrusive lava dome. The relationships in the area are very complex.

A linear body of similar quartz-feldspar porphyry which may be in part, extrusive, can be traced from Lobstick Bay west to Long Bay (Figure 1.32).

South of the linear porphyry body, along the northern shore of Lobstick Bay and within the eastern end of Long Bay, proximal deposited pyroclastic rocks occur (Figure 1.32). These rocks are generally coarse, clastic, and homolitic with the main clast type being an angular to subangular quartz-feldspar porphyry that is lithologically similar to the porphyry bodies. Beds of mafic pumice-bearing, fine-grained

tuff occur within the homolitic sequence. The pyroclastic units are matrix- to clast-supported, and poor to well bedded. Some of the beds have characteristics similar to the model developed by Wright *et al.* (1981) and Sparks *et al.* (1973) for subaerial pyroclastic flows (Figure 1.3). Clastic horizons are bounded by thin fine-grained tuff zones, which could be ground surge or cloud surge deposits, or both. Many depositional features seen in this facies cannot be explained by debris flow emplacement and may have a primary depositional origin.

If the vent facies porphyry is a volcanic dome and the lateral porphyry a flow, then explosive activity from the end of the flow would account for the proximal deposition facies rocks in Long Bay. Rose *et al.* (1976) have documented explosive activity from andesite flow fronts on the flank of the endogenous dome at Santiaguito in Guatemala.

Epiclastic rocks that may or may not be directly associated with the Berry River formation are found west of Mist Inlet. These well bedded wackes, many of which exhibit good Bouma Sequences (Bouma 1962), are more quartz-rich than the other wackes of the Warclub group. Rounded quartz grains are slightly larger than the associated plagioclase feldspar and lithic grains in these wackes. These quartz-rich wackes may be the distal equivalent of reworked debris flows and volcanic debris flows of the Berry River formation that were deposited by turbidity currents.

VOLCANIC FACIES AND KNOWN MASSIVE-SULPHIDE DEPOSITS

The previous two examples of Archean volcanological facies are of rocks containing no known massive-sulphide deposits. The potential for base-metal mineralization in Bryce Township is high, and there is also potential at the eastern end of the Berry River formation.

Examples of known massive-sulphide deposits in the Noranda area of Quebec can be recognized within a particular volcanic facies. The Millenbach and Corbet Mines are 8 km north of the city of Rouyn-Noranda, Quebec. The Millenbach Mine is associated with subaqueous quartz-feldspar porphyry bodies and the Corbet Mine is related to coarse phreatic breccia in mafic metavolcanics. Both deposits are in a vent facies environment.

The Millenbach Deposit

The Millenbach deposit consists of 15 massive-sulphide lenses located on and around a quartz-feldspar porphyry (Knuckey, Comba, and Riverin 1982). The quartz-feldspar porphyry was extruded from three or more vents along a northeast-trending feeder system (Comba and Gibson 1983). It was extruded endogenously and as flow lobes over a length of 2 km. The thickest parts of the porphyry body are over the main vents (Comba and Gibson 1983).

The Millenbach volcano consisted of an upper and lower part known as the upper QFP and the lower QFP, as shown in Figure 1.36 from the paper by Knuckey, Comba, and Riverin (1982). The lower QFP was extruded on the thin Millenbach andesite which

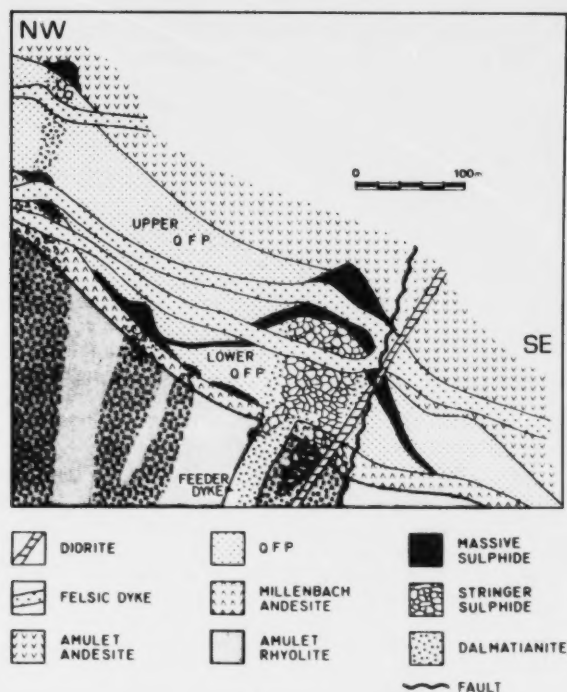


Figure 1.33. Geology of the Millenbach deposit, looking northeast along a northwest-southwest section. (From Knuckey et al. 1982, Figure 6).

overlies the Amulet Rhyolite (Figure 1.33). The lower QFP formed a hummocky ridge 760 m by 300m and up to 110 m thick. The main orebody was deposited on the upper surface of the lower QFP together with a local cherty horizon (Knuckey, Comba, and Riverin 1982). The upper QFP may have been coeval or slightly younger and was extruded to the northwest of the lower QFP and locally overlapped it. A small lens of massive sulphide was deposited on top of the upper QFP in an area of constant hot spring activity just northwest of the main centre. A local cherty exhalite is associated with these sulphides.

Deep-seated northeast-trending syn-volcanic faults controlled the quartz-feldspar porphyry (QFP) volcanism and the ore-forming hydrothermal solutions. Breccia associated with the extrusive QFP is not believed to be phreatic, but rather the result of syn-volcanic slumping (Comba and Gibson 1983).

The Corbet Mine

Although phreatic breccias are not associated with the Millenbach Mine, they are related to mineralization at the Corbet Mine. This mine is 1000 m lower in the Noranda area stratigraphy than the Millenbach Mine. The Corbet Mine is located within the top 250 m of the Flavrian andesite, as shown in Figure 1.34 from the paper by Knuckey and Watkins (1982). Figure 1.34 is a section through a part of the Corbet

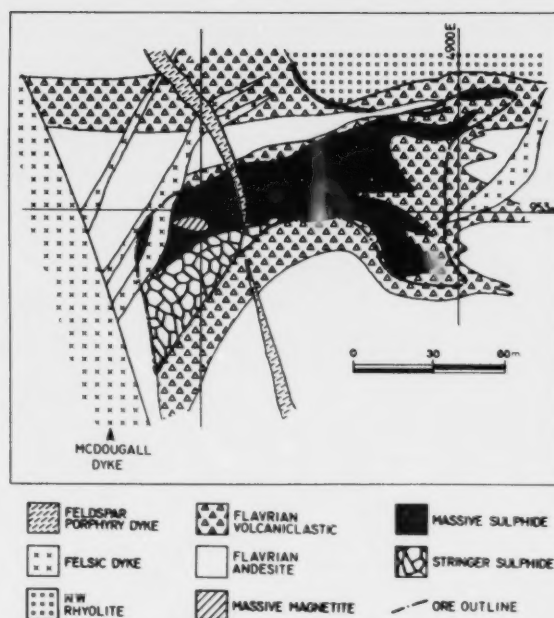


Figure 1.34. Geology through the Corbet Mine, looking north along section 800 N. (From Knuckey and Watkins 1982, Figure 1).

Mine. The breccia (Flavrian volcaniclastic, Figure 1.34) is composed of *in-situ* flow breccia grading to highly vesiculated andesite debris consisting of unsorted, angular to subangular fragments set in a microbreccia matrix. Locally, there is a weak layering and occasional grading. This debris locally reaches thicknesses of up to 100 m. Clasts composed of new magma are not found within this breccia (Knuckey and Watkins 1982). This breccia is probably a phreatic breccia.

A roughly concordant quartz-diorite sill stratigraphically below the orebodies has domed the Flavrian andesites. This sill was intruded syn-volcanically and acted as a heat source to circulate hydrothermal fluids (Knuckey and Watkins 1982). Initial heat required for the formation of the phreatic breccias would likely have come from rising magma forming the mafic flows. During formation of the massive-sulphide lenses, the overlying mafic flows encrusted the active vent resulting in the formation of smaller sulphide lenses above the main body (Knuckey and Watkins 1982; Figure 1.34).

DISCUSSION

These two examples show that volcanogenic massive-sulphide deposits occur in both felsic to intermediate and mafic metavolcanic environments. Sulphide horizons tend to be localized over the discharge vents of submarine hydrothermal systems, which are most likely in proximal and vent facies environments. Subvolcanic intrusions are a significant

TABLE 1.15: EXPLORATION CRITERIA FOR ARCHEAN VOLCANOGENIC MASSIVE-SULPHIDE DEPOSITS.

EXPLORATION CRITERIA			
REQUIREMENT OF MODEL	GENERAL	SPECIFIC	VOLCANIC FACIES
Heat	- near surface magma	- volcanotectonic depression - exposed central intrusion or underlying sill - abundant dikes	vent and/or proximal
Self-sealing cap rock	- phreatic explosion products	- coarse lithic fragment breccia with altered mineralized clasts	vent
	- evidence of relatively shallow water (<500 m)	- vesicular, texturally complex lavas, pyroclastic rocks, hyaloclastite	proximal
Cross-stratigraphic permeability	synvolcanic faults	- structures filled with synvolcanic dikes	vent and/or proximal
		- alignment of structurally localized features, (eg. domes, sulphide deposits, dike swarms)	vent to proximal
		- alignment of rapid thickness of facies changes in units (flows, slump breccias, ponded sediments)	proximal
		- clastic sediments derived from erosion of unstable fault scarps, mud flow breccia, conglomerate	proximal to distal

feature, acting as a source of heat for the hydrothermal systems, and possibly causing phreatic and phreatomagmatic eruptions. Franklin *et al.* (1981) estimated that the subvolcanic intrusive body must have had a volume of several km³ in order to sustain a hydrothermal circulation system large and long enough to form an orebody.

Hodgson and Lydon (1977) have discussed volcanogenic massive-sulphide deposits and their association with active hydrothermal systems. These authors have outlined the exploration implications for such deposit types (Table 2 in Hodgson and Lydon 1977). Table 1.15 is adapted from their table, and is an attempt to assign a facies concept to some of the features they noted in their table.

The assignment of volcanic facies in the eastern Lake of the Woods area (Figure 1.32) and the Skead Group pyroclastic rocks (Figure 1.31) was made from data collected from 1:15 840 scale mapping. Data gathered from a single outcrop or small claim group is generally not sufficient to permit accurate interpretation of a facies, and must be combined with all the information available from a region before meaningful trends can be established.

SUMMARY

Knowledge of volcanic facies is of potential use in mineral exploration, both in helping to understand how orebodies are formed in volcanic terrains, and in developing new techniques to explore for them. Knowledge of volcanic processes and volcanic rock classification are essential prerequisites to the study of volcanic facies. The overview presented here should not be taken as the final word, but rather as an introduction to the rapidly developing field of activity applicable to Archean volcanism and ore-genesis.

ACKNOWLEDGMENTS

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Chapter 2

Stratigraphic Correlation Techniques

N.F. Trowell

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ABSTRACT

Volcanic rocks are by nature complex, and have highly variable modes of eruption, physical and chemical attributes, and resultant landforms and surface features. Observation of modern volcanic rocks provides insight into their form and environmental setting, but precise correlation, even in these rocks, is difficult. Archean volcanic rocks viewed only in two-dimensions, present many additional problems. For example, the asymmetric, discontinuous, and variable shapes of volcanic units are further complicated by erosion, deformation, and metamorphism. This, coupled with generally discontinuous exposure, makes such features as calderas and cauldrons extremely difficult to recognize. Walking out stratigraphic units is generally impossible due to their lenticular form and limited areal extent. Many rules that apply to stratigraphic interpretation in sedimentary assemblages must be applied cautiously. Abrupt changes of strike and dip and unconformities may have little structural significance. For this reason, correlation techniques used in Archean terrains differ somewhat from those used in conventional stratigraphy.

Correlation can be made by use of stratigraphic marker horizons such as variolitic flows, interflow chemical sediments, and distinctive tephra layers. Volcanic rocks can be assigned to specific chemical suites. Recognition of komatiitic volcanic rocks in the Abitibi Belt has allowed the correlation of both local and regional stratigraphic sequences. Volcanic rocks can be assigned to facies by delineating physical and structural features related to distance from eruptive centres. Flows commonly exhibit certain intrinsic geophysical properties. It is possible to trace and distinguish between high-Fe and high-Mg tholeiitic flows on the basis of their magnetic signature.

Recently, radiometric ages have proven to be powerful tools both in defining local stratigraphy and in regional correlation.

The importance of stratigraphic studies to Archean mineral exploration can be demonstrated by analogy with the Kuroko base-metal deposits. These are confined to specific stratigraphic felsic volcanic sequences, and paleontological evidence suggests that deposits as widely separate as 300 km formed simultaneously.

INTRODUCTION

This chapter will discuss a few techniques used for the correlation of volcanic rocks specifically with reference and application to deformed and metamorphosed Archean terrains.

Volcanic rocks are by their very nature complex. As one goes further and further back in geologic time, it becomes increasingly difficult to:

1. reconstruct volcanic sequences
2. correlate volcanic deposits

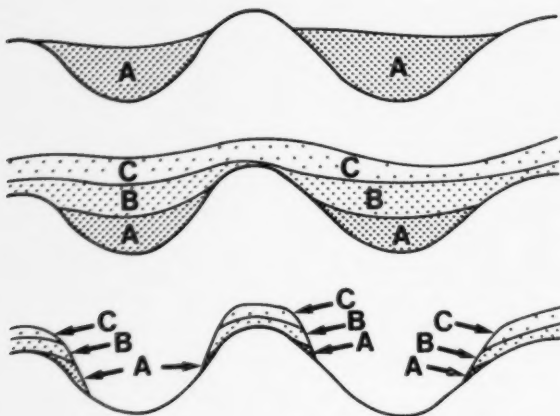


Figure 2.1. Differential erosion of a sequence of ash flows.

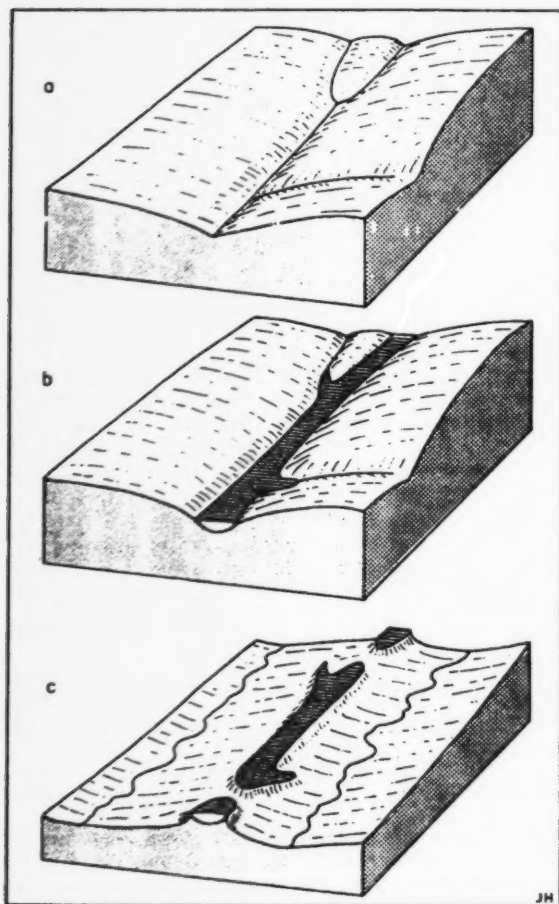
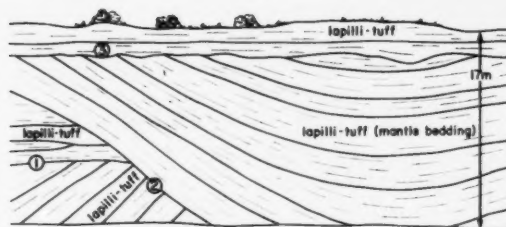


Figure 2.2. Differential erosion leading to inversion of relief.



Pyroclastic Deposits, St. Vincent (East Coast)

Figure 2.3. Schematic diagram of pyroclastic deposits from St. Vincent's.

3. determine the geologic setting in which they were erupted.

One of the prime reasons for this lack of knowledge is the fact that volcanic rocks often form constructional topographic features which inevitably leads to their relatively rapid destruction by erosion. By contrast, the deposition of sedimentary rocks in protected basins can preserve thick stratigraphic sections, completely documenting geological events over tens of millions of years.

Assuming that physical and chemical laws are immutable, one should first look at examples of the morphology of younger volcanoes and their products to gain insight into the types of problems inherent in correlating Archean strata. These examples are from the subaerial environment, but beyond doubt, similar processes operate subaqueously.

THE NATURE OF VOLCANIC STRATIGRAPHY

Contrasting mechanical properties of volcanic rocks often produce classic examples of differential erosion. An example of how an area could be misinterpreted after erosion is shown in Figure 2.1. A lower ash flow unit (top illustration) has filled in the pre-existing topography, but was not extensive enough to cover the ridge crests. The degree of compaction of ash flows is a function of their thickness, and thus will be greatest in areas of negative relief as the ash flows "fill-in" the topography. Subsequent ash flows (middle illustration) would tend to follow the same paths, but erosion due to water and/or ice along the valleys might completely scour out those deposits leaving the situation seen in the bottom illustration.

Any volumetric calculations, stratigraphic sections, and attempted correlations based on a limited exposure of such terrain would be very misleading.

Figure 2.2 illustrates how erosion can cause an inversion of relief. A basaltic lava flow (lined pattern) that occupied a valley bottom is more competent and thus less easily eroded than the underlying bedrock. Because of this contrast, the final configuration after stream erosion is a string of basalt-capped hills (bottom illustration).

Figure 2.3 is a schematic diagram showing a sequence of pyroclastic deposits from St. Vincent's. What significance does the steep erosional unconformity have? It may in fact represent only a short period of time during eruptive activity. Abrupt variations in dip over short distances due to mantle

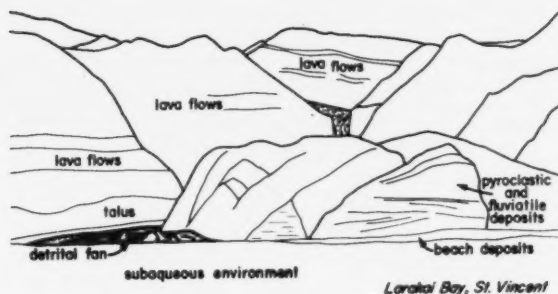


Figure 2.4. Schematic diagram of volcanic deposits from St. Vincent's showing different volcanic environments.

bedding are meaningful on only the local scale and have no structural significance. Of course, one never sees excellent exposures like this in Archean terrain. This increases these problems of structural interpretation several-fold.

Figure 2.4, a schematic diagram, also of volcanic deposits from St. Vincent's, illustrates how different volcanic environments and their product lithologies can occur together in one relatively restricted area. Active erosion of constructional topographic features is occurring as is shown by formation of the alluvial deposits. An Archean analogue in which a similar area was eroded, covered by younger deposits and then deformed, would obviously be very difficult to interpret, especially where only a two-dimensional view is available.

The question of erosion is one of critical importance, specifically for pyroclastic rocks which tend to form constructional topographic land forms. As Ayres has recently pointed out (Ayres 1983), from 2x to 4x the observed volume of felsic volcanic rocks in his study area of Archean rocks had been eroded to provide detritus to subjacent sedimentary environments.

In many cases it may not be possible to do extended correlations in areas having only partial volcanological records.

EXAMPLES OF STRATIGRAPHIC CORRELATION FROM ARCHEAN TERRAINS

Table 2.1 is a listing of some of the correlation techniques used in Archean terrains. Discussion of these techniques will be brief, but will provide an introduction to more detailed descriptions in the accompanying chapters of this volume.

STRATIGRAPHIC MARKER HORIZONS

Figure 2.5 from Green (1975) shows a distinctive glomeroporphyritic horizon that can be traced for several km in the Kneé Lake area of Manitoba. Similarly, variolitic horizons in the Abitibi Belt of Ontario and Quebec can be traced for distances in excess of

TABLE 2.1: CORRELATION TECHNIQUES IN THE ARCHEAN.

STRATIGRAPHIC MARKER HORIZONS

Glomeroporphyritic, variolitic flows
Interflow sediments/pyroclastics

CHEMOSTRATIGRAPHIC CORRELATION

STATISTICAL CORRELATION

INTRAVOLCANIC SEDIMENTS

Stromatolites
Iron Formation

GEOPHYSICAL CORRELATION

GEOCHRONOLOGY

70 km. It should be kept in mind, however, that it is not one individual flow that is being traced, but rather a stratigraphic package wherein variolitic or glomeroporphyritic lavas are the dominant volcanic products. Since these flow types are not rare, caution should always be exercised to ensure that it is the same stratigraphic package being correlated.

In the Mattagami area of Quebec (Figure 2.6 after Costa *et al.* 1983), on the southern limb of the Allard Anticline, the lower Watson Lake Group consists of felsic flows and pyroclastic rocks. It is separated from the overlying Wabasee Group of both mafic flows and felsic pyroclastic rocks by the "Key Tuffite" horizon. The Key Tuffite horizon consists of chemical sediment and airfall ash material. Not only is the Key Tuffite horizon important for correlation purposes, but it also overlies the orebodies of Mattagami, Orchan, and Bell Allard, making it a prime target in mineral exploration. Furthermore, its presence allowed Roberts (1975) to do a palimpsestic reconstruction of the paleotopography and paleoenvironment of ore deposition. Recognition of the airfall ash component of this unit is an example, albeit on a local scale, of the more specialized correlation technique of tephrochronology.

CHEMOSTRATIGRAPHIC CORRELATION

Volcanic rocks can be assigned to specific chemical suites based on field and laboratory criteria.

In the Savant Lake-Crow Lake area of Northwestern Ontario (Figure 2.7), local stratigraphy was deciphered and volcanic sequences were assigned an approximate chemical composition on the basis of field determination of mafic mineral content (Trowell *et al.* 1980). Subsequent chemical data allowed for both the assignment of these sequences to their respective chemical suites (Figure 2.8), and the recognition of specific stratigraphic distribution patterns based on those suites. Correlation of discontinuous sequences in this area still relied, however, on other means, specifically, geochronology to demonstrate the time relationships between these suites.

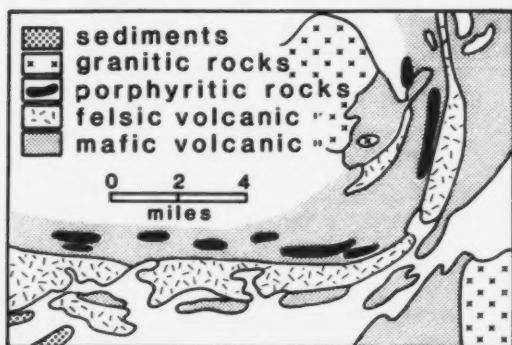


Figure 2.5. Knee Lake area of Manitoba showing distinctive marker horizons (porphyritic rocks).

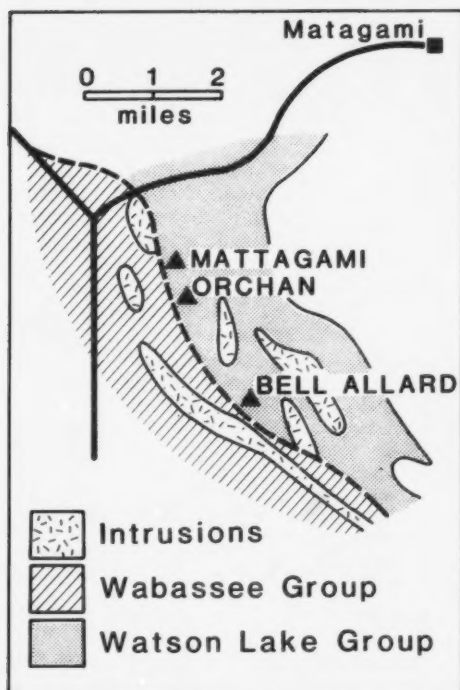


Figure 2.6. Mattagami area of Quebec illustrating importance of stratigraphic marker horizons in mineral exploration.

STATISTICAL CORRELATION

During the process of analyzing volcanic rocks, statistical manipulation of qualitative data is used to predict stratigraphic relationships and correlations. In the Kirkland Lake area, Hyde (1978) has successfully used Markov Chain Analysis, a statistical technique, in the study of the alkalic volcanic rocks of the Timiskaming Group. Figure 2.9 shows a measured section of pyroclastic rocks that have been assigned to their respective facies whether airfall, ash flow, or reworked. Statistically, it is possible to estimate the

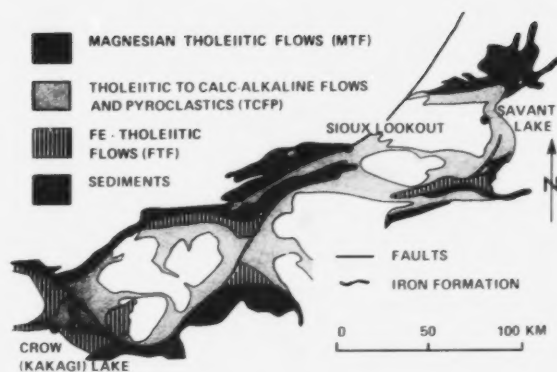


Figure 2.7. Sketch map showing broad lithostratigraphic relationships of Savant Lake-Crow Lake area.

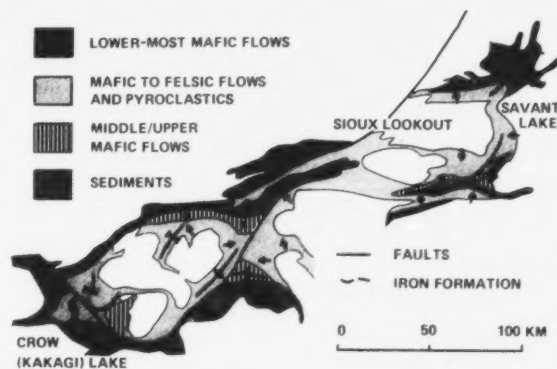


Figure 2.8. Sketch map to show distribution of volcanic suites in the Savant Lake-Crow Lake area.

probability of one facies succeeding another in the stratigraphic section.

This method should prove to be very helpful in the correlation of areas where exposure is poor, and it could have applications for mineral exploration if, for example, one particular facies is deemed to have an high mineral potential.

INTRAVOLCANIC SEDIMENTS AND BIO-CORRELATION

While it probably can be said that the Archean record does not abound in fossils, it is to the Archean that we must look for the earliest traces of life. At present, stromatolites are the only abundant fossils recognized in the Archean rocks of Ontario that can be used for bio-correlation.

Archean stromatolites are known to be present at several localities in Ontario (Table 2.2). More occurrences are likely to exist. Attendant upon future finds, detailed studies of their morphology may permit the recognition of specific assemblages, useful, not only

for purposes of correlation, but also for more detailed palaeoenvironment and palaeogeography analysis.

Microfossils have been documented in rocks as old as the 3500 Ma year old Warrawoona Group of Western Australia. Recently, laminated algal mats and stromatolites have been identified in the Helen iron formation at Wawa, suggesting that they may hold some promise as a correlation tool of the future. The chapter on the stratigraphy of the Western Uchi Subprovince (Chapter 6, this volume) will discuss how stromatolitic horizons might be used as potential correlation tools, and will illustrate some of the pitfalls inherent in correlating apparently similar though widely separate stromatolitic units.

INTRAVOLCANIC IRON FORMATION

Due to their great lateral extent, intravolcanic iron formations can be used to correlate separate and discontinuous volcanic sequences. In the chapter on the Wawa area (Chapter 4, this volume), an extended discussion is given on the use of Michipicoten-type iron formations in the correlation of volcanic sequences in a region that has suffered extensive faulting.

Even though neither stromatolites nor iron formations are volcanic rocks, for the purposes of regional correlation, all the tools available should be used. Even simply determining that two widely separated volcanic sequences are older or younger than a specific, laterally continuous, intravolcanic sedimentary unit is an important first step in refining regional correlation within the Superior Province.

GEOPHYSICAL CORRELATION

One example of geophysical correlation is the use of aeromagnetic data to distinguish and trace packages of volcanic rocks with distinct chemical and therefore physical characteristics over a part of the Abitibi Belt straddling the Porcupine-Destor Break (see Letros *et al.* 1983).

Figure 2.10 is a schematic diagram of a first derivative vertical gradient map of aeromagnetic data. Packages of rocks, in this case magnesian tholeiites and high-iron tholeiitic basalts, can be distinguished on the basis of a particular geophysical parameter, in this case magnetic susceptibility.

GEOCHRONOLOGY

Correlation of local Archean sequences on a regional to geological subprovince- and province-wide scale has, until the present, relied upon similarities in lithologies and recognition of extensive sedimentary or tectonic events. Lithocorrelation is, however, restricted by the extent of the lithostratigraphic units in question. This limits the reliability of such regional correlations.

Recently, radiometric age determination methods have proven to be powerful tools both in defining local stratigraphy and regional correlation. The importance of geochronologic studies to Archean mineral exploration can be demonstrated by an analogy with the Kuroko base-metal deposits. These deposits are confined to specific stratigraphic felsic volcanic sequences; both paleontological and paleomagnetic

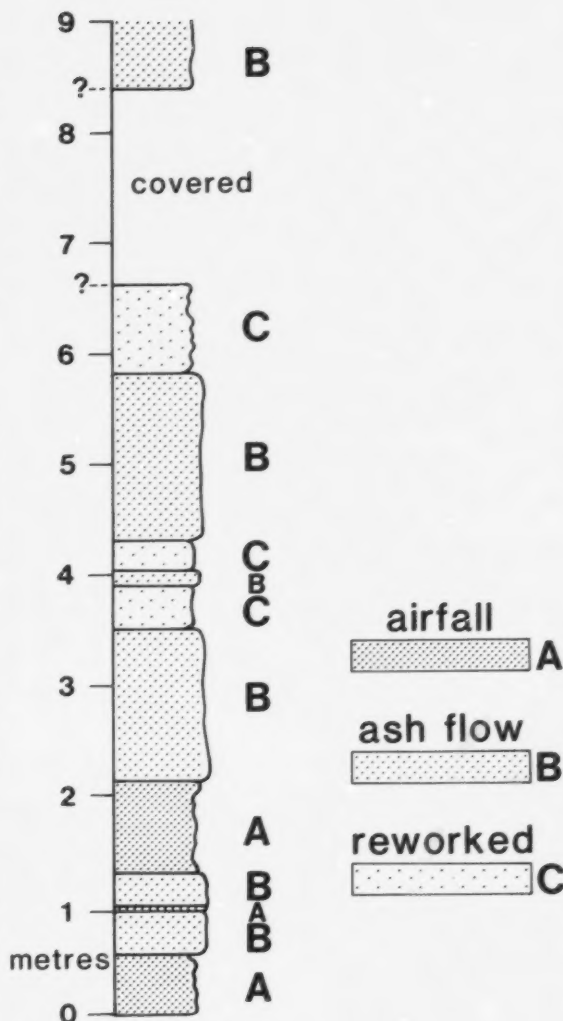


Figure 2.9. Measured section of pyroclastic rocks in the Kirkland Lake area (after Hyde 1978).

TABLE 2.2: STROMATOLITE OCCURRENCES IN SUPERIOR PROVINCE OF ONTARIO.

Woman Lake	Uchi
Red Lake	Subprovince
Steeprock	Wabigoon
	Subprovince
Kirkland Lake?	Abitibi-Wawa
Wawa	Subprovince

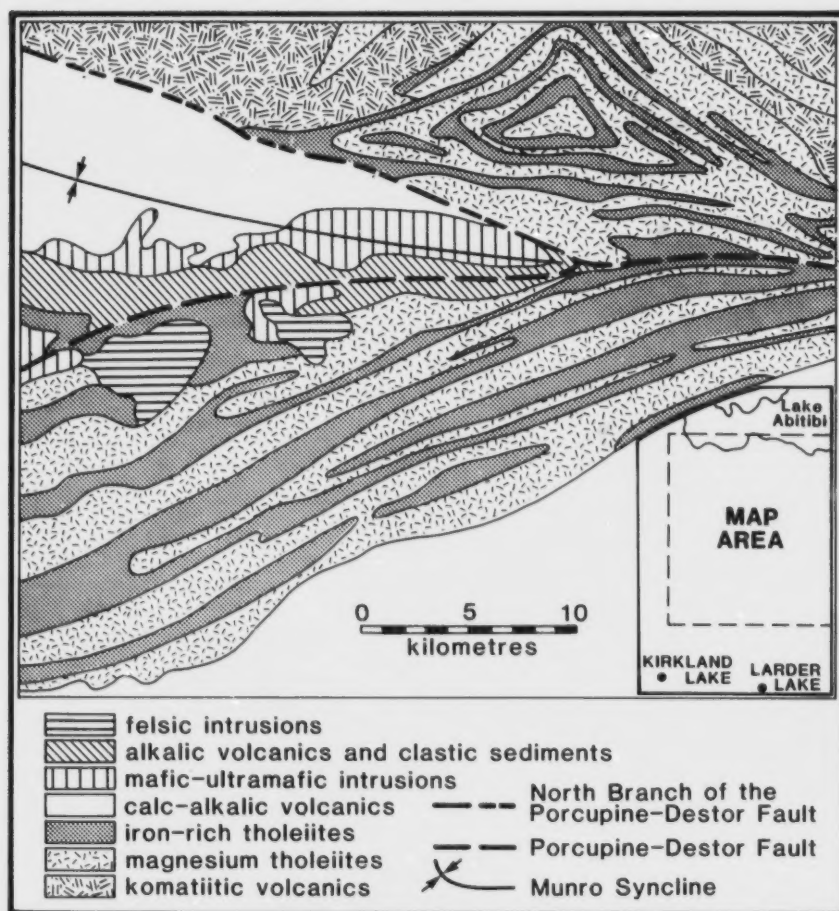


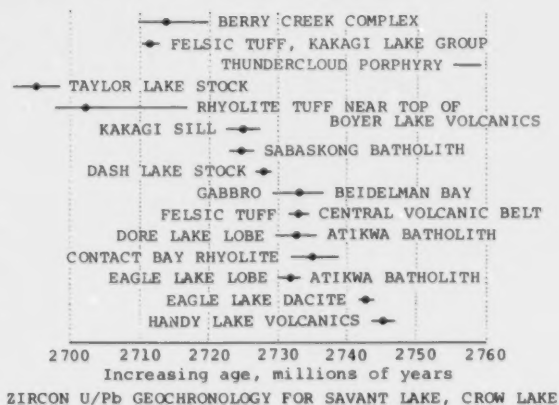
Figure 2.10. Schematic of first derivation vertical aeromagnetic data over part of Abitibi Belt illustrating how different volcanic suites can be distinguished on the basis of their magnetic character.

evidence suggests that deposits separated by as much as 300 km. formed simultaneously (Scott 1980; Ueno 1975). With this in mind, a geochronologic study (Davis and Edwards 1982; Davis and Trowell 1982; Davis *et al.* 1982) was done in the Savant Lake-Crow Lake area of Northwestern Ontario to bracket the time of formation of the Sturgeon Lake base-metal deposits, and to compare this age with the ages of other volcanic sequences throughout the belt (Table 2.3). This study is being continued by the private sector.

A WORD ABOUT SCALE

When mapping at a scale of 1:15 840, it is highly fortuitous if individual flows or pyroclastic horizons can be traced for an appreciable distance. Under favourable conditions, however, packages of units can be correlated between traverse lines. A mineral explorationist, for whom a 1/4 mile can represent the surface extent of a viable mineral deposit, may find it necessary to correlate to the outcrop scale. Hence, the precision required and attained in correlation depends very much on the purpose of the geologist involved and the amount of time and effort he is willing to expend.

TABLE 2.3: ZIRCON U/PB GEOCHRONOLOGY FOR SAVANT LAKE.



Whatever the scale, it will be the education, experience, and skill of the field mapper that will ultimately determine the quality of any stratigraphic correlation.

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Part Two: Volcanic Stratigraphy in Archean Greenstone Belts

Chapter 3

Stratigraphic Correlation of the Western Wabigoon Subprovince, Northwestern Ontario

N.F. Trowell and G.W. Johns

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ABSTRACT

The Savant Lake-Crow Lake metavolcanic-metasedimentary belt extends for 300 km within the western part of the Wabigoon Subprovince. Correlation of stratigraphy in this area was initially made on the basis of the following observations: 1) general inward facing of metavolcanic-metasedimentary sequences; 2) thick basal mafic assemblages are all situated at the outer edges of the belt; 3) overlying, mixed mafic to felsic sequences are more internal and contain thick assemblages of mafic flows that are mostly toward or at the top of these sequences, and in some places may be allochthonous; 4) association of clastic sedimentary rocks with mixed mafic to felsic parts of volcanic sequences; and 5) lateral continuity of certain ironstone-bearing formations.

Recent mapping has extended the correlation of stratigraphy into the Gibi Lake and Lobstick Bay-Lake of the Woods area.

Local and regional geochemical studies support the stratigraphic relationships outlined. Geochronology has also been used successfully to refine the stratigraphy.

Local and regional mapping, combined with lithogeochemical syntheses and geochronological studies have produced a much clearer picture of the geological evolution of this area. Future studies will allow placement of mineral deposits of this area into this new tectonostratigraphic framework.

INTRODUCTION

A 300 km long metavolcanic-metasedimentary belt (Figure 3.1), stretching from Savant Lake in the east to the eastern part of Lake of the Woods in the west, forms the western end of the Wabigoon Subprovince (Mackasey *et al.* 1974).

The Wabigoon Subprovince is a major tectonostratigraphic subdivision of the Superior Province, consisting of belts of predominantly metavolcanic rocks and subordinate metasedimentary rocks intruded by granitoid bodies, some of batholithic dimensions. It is bordered to the north and south by the English River and Quetico Subprovinces, respectively, which consist mainly of metasediments, migmatite, and granitic rocks of both anatectic and magmatic origin.

In the 1960s, Goodwin (1965) compared and correlated volcanic stratigraphic sections on the basis of their geochemistry and suggested a two-fold subdivision of the volcanic sequences at Lake of the Woods. Goodwin found no such evidence for a two-fold subdivision elsewhere in the eastern half of the area under discussion: in this area he concluded that only the lower subdivision was present.

In the 1970s, H.D.B. Wilson and coworkers (Wilson *et al.* 1974; Wilson and Morrice 1977; Morrice

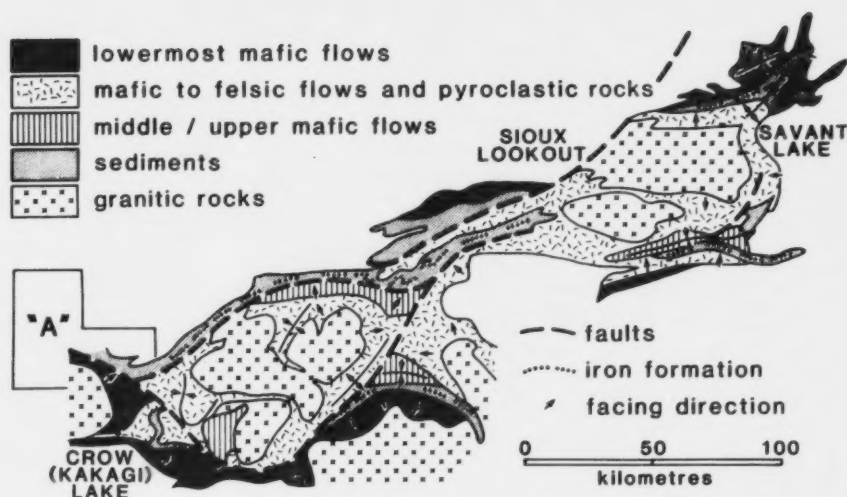


Figure 3.1. Sketch map showing broad lithostratigraphic relationships and structural complexity of the Savant Lake-Crow Lake area. Area "A" is the recently mapped Long Bay-Lobstick Bay area.

1977) studied the volcanic and sedimentary stratigraphy of the western Wabigoon Subprovince. These authors proposed a four-fold sequential model based upon comparable sequences in Archean greenstone terrains of South Africa and Australia. They attempted to apply this model to the area from Lake of the Woods to Sturgeon Lake on the basis of literature reviews and mapping of selected sections.

In the 1970s, N.F. Trowell, C.E. Blackburn, and G.R. Edwards of the Ontario Geological Survey conducted a synoptic study of the metavolcanic sequences from Crow (Kakagi) Lake to Savant Lake, emphasizing lithogeochemistry across recognized stratigraphic sections. Among their conclusions, Trowell, Blackburn, and Edwards (1980) found that the four-fold subdivision proposed by Wilson and coworkers was not tenable, but that there was a general succession of lithogeochemically distinct sequences throughout the area.

A geochronological program carried out under the direction of D.W. Davis of the Royal Ontario Museum in the late 1970s and early 1980s, allowed for refinement of correlation of volcanic sequences throughout the belt (Davis, Blackburn, and Krogh 1982; Davis and Trowell 1982; Davis and Edwards 1982).

Further work by Trowell, Logothetis, and Caldwell (1980), Trowell (in preparation), and Johns (1981, 1982, 1983) has provided more detailed information on the stratigraphy and lithogeochemistry of the eastern part of the Lake of the Woods area. This chapter represents a synopsis of that work intended to show how lithogeochemistry and geochronology can be used as correlation tools in deciphering Archean terrains. Wherever possible, the reader is referred to previous publications for details of local stratigraphy. Since information on the eastern Lake of the Woods area is new and as yet unpublished, a more complete description of that stratigraphy as interpreted from recent mapping by Johns and Richey (1982), Johns and Davison (1983), Johns, Good, and Davison (1984) is provided in this chapter.

CHEMOSTRATIGRAPHIC CORRELATION

In any attempt at regional correlation based upon the chemical character of local stratigraphic sections, the following reservations must be kept in mind. Firstly, the present state of detailed mapping is such that in most cases individual sequences have not yet been traced between geographic areas. Secondly, sequences are disrupted, both by tectonism and by batholithic intrusion. Sense and movement on long faults are not well documented. Emplacement of large granitic bodies have likely removed voluminous amounts of volcanic rock by stoping, particularly from the basal parts of these volcanic sequences. Lastly, stratigraphic sequences in one geographic area, with particular chemical affinities are not necessarily time-equivalent to lithologic packages exhibiting similar chemical characteristics in other areas.

Figure 3.1 (from Trowell, Blackburn, and Edwards 1980) illustrates a tentative correlation of the main part of the metavolcanic metasedimentary belt, while Figure 3.2 outlines the recently interpreted stratigraphy at the western end of the Wabigoon Subprovince in the Lake of the Woods area. These correlations were made based on tracing marker horizons, and on general comparison of lithologic characteristics prior to obtaining significant amounts of chemical data.

Five general observations are of paramount importance in making this preliminary correlation. These are:

1. Discounting the many reversals due to folding, doming due to batholithic emplacement, and complications due to faulting, it can be noted that sequences predominantly face inward toward the axis of the belt. In particular, volcanic rocks near the contact with enclosing batholiths invariably face inward.
2. In the lower stratigraphic sequences, thick successions of mafic flows are invariably situated at the margins of the belt.
3. Away from the margins of the belt, highly variable sequences of mafic to felsic flows and

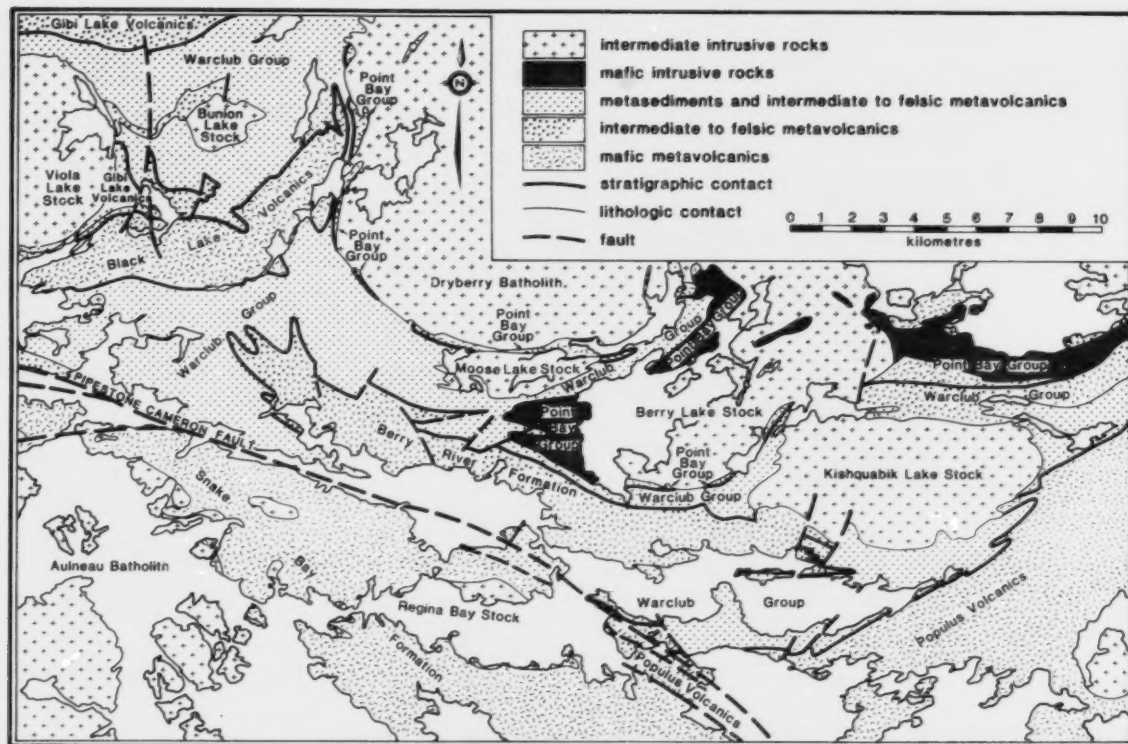


Figure 3.2. Stratigraphic map of the Long Bay-Lobstick Bay area. The area is structurally complex due to the intrusion of the Aulneau and Dryberry Batholiths and the Viola Lake Stock.

pyroclastic rocks predominate. Where thick accumulations of mafic flows occur in these upper volcanic sequences, they are found at or near the very top.

4. Thick sequences of clastic sedimentary rocks are associated both laterally and vertically with the volcanic sequences containing mafic to felsic flows and pyroclastic rocks. In contrast, few sedimentary rocks are associated with the thick mafic successions in either the lower or upper sequences.
5. Iron formations, predominantly oxide facies, occur discontinuously within the clastic sedimentary zones. It is probable that within each sedimentary zone, the iron formation units are correlative.

The general geology of the main part of this belt was described previously (Trowell, Blackburn, and Edwards 1980, p.2-6; Blackburn *et al.* 1982). Mapping since then (Johns and Richey 1982; Johns and Davison 1983; Johns, Good, and Davison 1984) has provided us with a more detailed and accurate knowledge of the far western part of the belt, and an expanded discussion on this subject is presented below.

LONG BAY – LOBSTICK BAY STRATIGRAPHY

To date, there has been no detailed stratigraphic subdivision of the Lake of the Woods part of the Wabigoon Subprovince. Mapping carried out between Lake of the Woods and the area studied by Trowell, Logothetis, and Caldwell (1980) at present permits a preliminary stratigraphic synthesis. Elements of the stratigraphy identified by Trowell, Blackburn, and Edwards (1980) have been recognized and may be used to extend correlations into the Lake of the Woods area. Further mapping is required, however, to subdivide the supracrustal sequences in the rest of the Lake of the Woods area.

Figure 3.2 is a lithostratigraphic map of the Long Bay Lobstick Bay area. The Snake Bay volcanics, Populus volcanics, and Warclub sediments outlined on Chart A in Trowell, Blackburn, and Edwards (1980) have been recognized in the Long Bay Lobstick Bay area. This area was subdivided into several geologic domains based upon their positions relative to the regional Pipestone-Cameron Fault and, to date, correlation has not been attempted between them.

Southwest of the Pipestone-Cameron Fault, the Snake Bay formation (Figure 3.2) is a north- to northeast-facing mafic metavolcanic sequence of fine-grained and medium-grained flows, fine-grained pillowed flows, and coarse massive and pillowed glomeroporphyritic flows. These flows are interdigitated with fine intermediate pyroclastic rocks in the

western part of the area. The base of the Snake Bay formation is in intrusive contact with the Aulneau Batholith, and the top may have been tectonically removed by the Pipestone-Cameron Fault.

Morrice (1977) was able to subdivide the Snake Bay formation into lower and middle mafic groups. Morrice's lower mafic group is 3650 m thick and has been subdivided into 12 formations. The middle mafic group is 6350 m thick and consists of 10 distinct formations (Morrice 1977). In the Long Bay-Lobstick Bay area, only the lower mafic group appears to be present.

Northeast of the Pipestone-Cameron Fault, six stratigraphic subdivisions within the supracrustal rocks may be discerned. These subdivisions are shown on Figure 3.2 as the Point Bay group, Populus volcanics, Black Lake volcanics, Gibi Lake volcanics, and Warclub group which includes the Berry River formation.

The presumed oldest supracrustal assemblage in the Long Bay Lobstick Bay area is the Point Bay group. This group has been largely intruded and assimilated by the Dryberry Batholith and only remnants are found rimming the contact. The Point Bay group is a diverse assemblage of highly metamorphosed mafic volcanic rocks, intermediate volcanic rocks, and metawackes intruded by thick, differentiated ultramafic to mafic sills. South of Dryberry Lake, the sequence is south facing, while west of the lake, it occurs in the nose of a series of folds. Roof pendants, discontinuous remnants, and xenoliths of this assemblage are found in the rocks of the Dryberry Batholith and Berry Lake Stock.

The Populus volcanics (Trowell, Blackburn, and Edwards 1980) are a largely northwest-facing sequence of massive and pillowed mafic flows, hyaloclastite, pillow breccia, and pyroclastic rocks with some interbedded intermediate pyroclastic rocks. These metavolcanics strike northeast from Dogpaw Lake where they have been juxtaposed against the Snake Bay formation by the Pipestone-Cameron Fault. The relationship between the Point Bay group and the Populus volcanics is unknown as there is no direct contact between them, but it can be assumed that the Populus volcanics are somewhat younger than the Point Bay group.

The Black Lake volcanics also bear an uncertain relationship to the Point Bay group. The Black Lake volcanics, which consist primarily of massive and pillowed mafic flows, occupy an anticlinal structure between Yellow Girl Bay and Bug Lake. Car (1980) completed a study in the western part of the Eastern Peninsula and hypothesized the existence of an Archean composite cone in that area. In the Adams River Bay area, coarse mafic debris flows, fine mafic tuff, wacke, and mafic flows are interbedded. This clastic sequence represents the distal part of the composite volcano hypothesized by Car (1980) overlying and interdigitated with mafic flows of the Black Lake volcanics. The Black Lake volcanics may represent flank flows from this prograding volcano, forming a platform on which the composite volcano continued to grow.

Figure 3.3 shows simplified stratigraphic sections in the Long Bay Lobstick Bay area. In the Gibi Lake

area, Trowell (in preparation) interpreted the stratigraphic sequence to be mafic flows of the Dogtooth Lake volcanics, overlain by wackes of the northern metasedimentary belt, overlain by the felsic and mafic pyroclastic rocks of the Gibi Lake volcanics. Mapping in the Long Bay-Lobstick Bay area has revealed a similar stratigraphic succession in the vicinity of Rat Lake (see Figures 3.2 and 3.3). Mafic flows of the Black Lake volcanics are overlain by a thin wacke sequence which is overlain by felsic to intermediate pyroclastic rocks. On the basis of stratigraphic similarity one of the authors (GWJ) correlates the Black Lake volcanics with the Dogtooth Lake volcanics and equates the pyroclastic rocks at Rat Lake with the Gibi Lake volcanics.

The Gibi Lake volcanics as defined by Trowell, Logothetis, and Caldwell (1980) occur in the northwestern part of Figure 3.2. Here, they are composed of intermediate to felsic pyroclastic rocks overlain by a mafic tuff unit. Within the Gibi Lake area (Trowell in preparation), the Gibi Lake volcanics consist of intercalated fine to medium, intermediate pyroclastic rocks, and fine mafic pyroclastic rocks. Around Rat Lake in the Long Bay-Lobstick Bay area, the felsic to intermediate pyroclastic rocks equated with the Gibi Lake volcanics are predominantly fine.

The Warclub group overlies all other stratigraphic subdivisions. Blackburn (1978) documented the existence of pyroclastic rocks within the Warclub Series of metasediments of Burwash (1934) and the Warclub sediments of Davies and Watowich (1958). Felsic to intermediate pyroclastic rocks are found interbedded with metasediments throughout the Long Bay-Lobstick Bay area. Since the structure and stratigraphy of the metasediments and the interbedded pyroclastic rocks is complex within the area, the author (GWJ) has grouped all of these rocks into the Warclub group.

There are a number of different metasedimentary rock types within the Warclub group: thinly bedded arenite and quartzose siltstone; interbedded arenite and wacke; wacke and magnetite ironstone; and wacke alone. These lithologies are found in a number of stratigraphic positions:

1. Thinly bedded arenite and quartzose siltstone overlie the Gibi Lake volcanics north of Yellow Lake.
2. Interbedded arenite and wacke underlie the Gibi Lake volcanics north of Graphic Lake (Trowell, 1984, in preparation).
3. Interbedded arenite and wacke overlie the Gibi Lake volcanics on Rat Lake.
4. Wacke and magnetite ironstone overlie the northern limb of the Black Lake volcanics at Bug Lake.
5. Wacke overlies the southern limb of the Black Lake volcanics.
6. Intermediate pyroclastic rocks and wacke overlie the Point Bay group south of Dryberry Lake.
7. Wacke overlies the Populus volcanics south of Dirtywater Lake.
8. Interbedded wacke and arenite, and wacke overlie and underlie the Berry River formation.

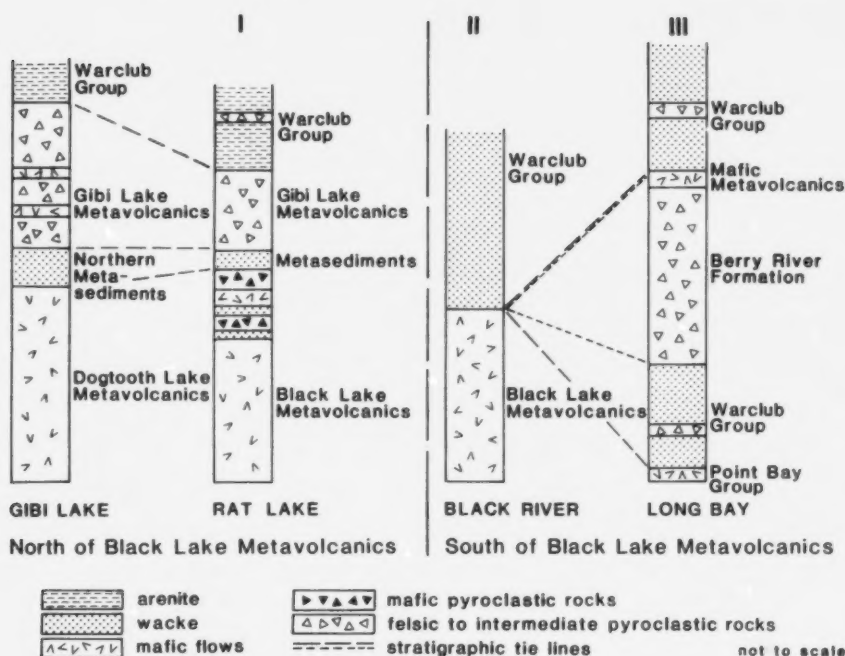


Figure 3.3. Simplified stratigraphic sections within the Long Bay-Lobstick Bay area. The Gibi Lake section is from work by Trowell (in preparation). Correlation between the Gibi Lake and Rat Lake sections is based on stratigraphic similarity.

9. Wacke interdigitates with and is probably the distal sedimentary equivalent of the Berry River formation northwest of Mist Inlet (see Figure 1.35, Chapter 1, this volume).

These lithologies, in their various stratigraphic positions, are commonly interbedded with intermediate pyroclastic rocks. Numerous formations may ultimately be defined within the Warclub group, and much additional work will be required to determine their inter-relationships. At this time, no coherent stratigraphic model exists to explain this sequence. It may be that within the Long Bay Lobstick Bay area, this group represents the interfingering of several sedimentary environments and periods of deposition.

The Berry River formation has been dated at 2713.9 Ma by Davis and Edwards (1982), and is assumed on the basis of its stratigraphic position to be younger than the Black Lake volcanics, Gibi Lake volcanics, and Point Bay group. South of Berry Lake, the Berry River formation is a south-facing homoclinal sequence within the Warclub group proper and overlies part of that group with slight unconformity.

The Berry River formation has been subdivided into volcanic facies (see Chapter 1, this volume). Two ages or events of deposition have been interpreted. A unit of quartz-feldspar porphyry associated with the younger age overlies rocks related to the older event. The younger event is believed to be located at the eastern extremity of the Berry River formation, south-east of Berry Lake.

LOCAL GEOCHEMICAL SYNTHESIS

A first evaluation of major element analyses (Trowell, Blackburn, and Edwards 1980) of more than 1000 samples supports and augments the general stratigraphic relationships outlined above. The authors have

also used 152 analyses from a previous study by Goodwin (1970) and 67 analyses by Morrice (1977).

Jensen cation plots (Jensen 1976) of the lower-most mafic volcanic sequences are shown in Figure 3.4. There is some scatter of the data, and no obvious trend from komatiitic to magnesian tholeiitic is present. These sequences were previously designated (Trowell, Blackburn, and Edwards 1980) as magnesian tholeiitic flows (MTF). Except for a few flows with komatiitic chemistry, there is no evidence (for example spinifex texture) to indicate the presence of true komatiites.

Mixed sequences of felsic to intermediate pyroclastic rocks and subordinate flows, and mafic flows and subordinate pyroclastic rocks are volumetrically the predominant volcanic assemblages in the study area. Plots for each of nine sections are given in Figure 3.5 (from Trowell, Blackburn, and Edwards 1980). New data for the Central Volcanic Belt is given in Figure 3.6 (from Blackburn *et al.* 1982). There is a considerable scatter of data points with samples falling in both the calc-alkalic and tholeiitic fields, but predominantly the calc-alkalic field. Because all suites contain samples that plot in the tholeiitic and calc-alkalic fields, these were designated (Trowell, Blackburn, and Edwards 1980) as tholeiitic to calc-alkalic flows and pyroclastic rocks (TCFP).

Plots from 5 thick upper mafic sequences are shown on Figure 3.7 (modified after Trowell, Blackburn, and Edwards 1980). Data from Morrice (1977) for the Snake Bay volcanics are presented in Figure 3.8.

Data presented by Morrice (1977) show that the rocks of the lower mafic group exhibit little or no chemical variation; K_2O content is very low, generally

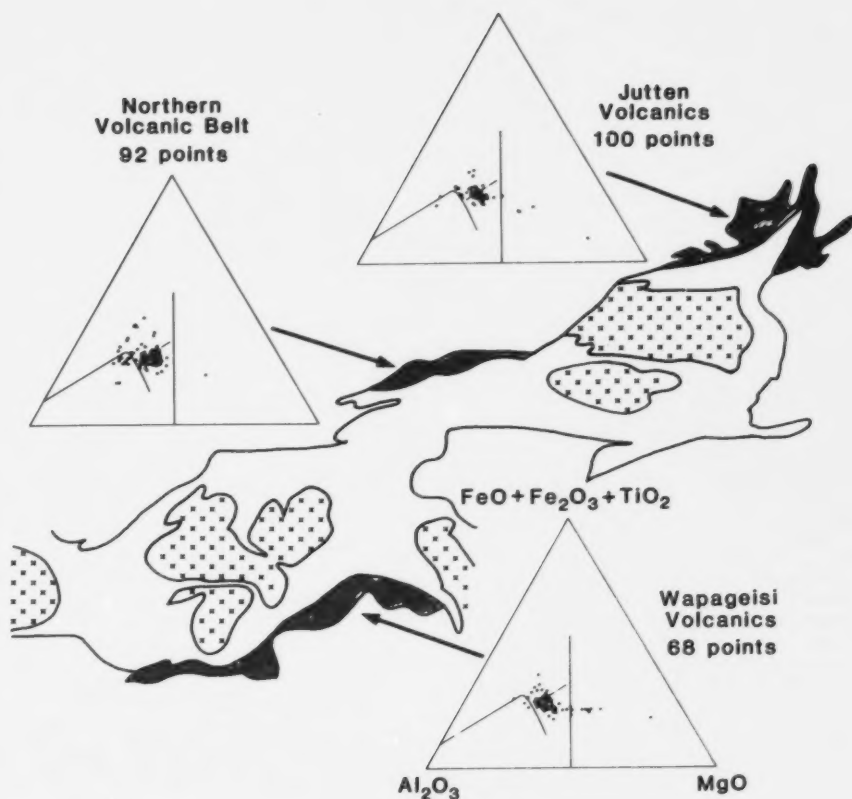


Figure 3.4. Jensen cation plot for Jutten volcanics, Northern volcanic Belt, and Wapageisi volcanics, showing their tholeiitic, relatively magnesian character (from Trowell, Blackburn, and Edwards 1980).

<0.10%; TiO_2 content is <1%; while FeO (total) is between 10% and 13%. With increasing stratigraphic height in the middle mafic group, Al_2O_3 , CaO, and MgO decrease in amount, while FeO (total), TiO_2 , Na_2O , and P_2O_5 increase.

Morrice's (1977) samples when plotted on the AFM ternary diagram of Irvine and Baragar (1971) and the Al-Fe-Mg cation plot of Jensen (1976) as shown in Figure 3.8, show that the lower mafic group and middle mafic group of flows are magnesium tholeiitic basalts and iron tholeiitic basalts, respectively.

As noted previously (Trowell, Blackburn, and Edwards 1980), the Katimiagamak Lake volcanics are at the base of the sequence in the Kakagi Lake area (Figure 3.7). While the Katimiagamak volcanics were then correlated with the entire Snake Bay formation, it would appear that chemically (Figure 3.8) they only compare with the middle mafic section of that formation. The lower mafic section of the Snake Bay Formation has not yet been correlated with any mafic metavolcanic suite in the immediate area.

Figures 3.7 and 3.8 show that although there is considerable scatter of data, the majority of samples fall in the tholeiitic field, with a tendency to be on the high-Fe side of the high-Mg/high-Fe divider. Also, in contrast to magnesium tholeiitic flow sequences, there is a tendency towards Fe enrichment. These assemblages were previously (Trowell, Blackburn,

and Edwards 1980) designated as Fe-tholeiitic flows (FTF).

REGIONAL GEOCHEMICAL SYNTHESIS

The distribution of the three types of volcanic suites is shown on Figure 3.9. Some general trends are apparent.

Lower mafic flow sequences are tholeiitic and, apart from Katimiagamak Lake and perhaps the middle mafic section of the Snake Bay Volcanics, they tend to be predominantly magnesian tholeiites. Middle mixed sequences of Figure 3.9 are highly variable and in general show a distinct calc-alkalic trend. Upper mafic flow sequences are predominantly Fe-tholeiitic.

GEOCHRONOLOGY

In an attempt to test, and in many cases refine the correlations proposed in the study area, a radiometric dating program using precise uranium-lead zircon ages was initiated in the late 1970s under the direction of D.W. Davis of the Royal Ontario Museum, Toronto. Several publications in the early 1980s (Davis *et al.* 1982; Davis and Trowell 1982; Davis and Edwards 1982) have presented numerous ages for various volcanic sequences and plutonic rocks throughout the study area. A summary of these ages is presented in Figure 3.10 (from Blackburn *et al.* 1982). As yet, none of the lower magnesian tholeiitic

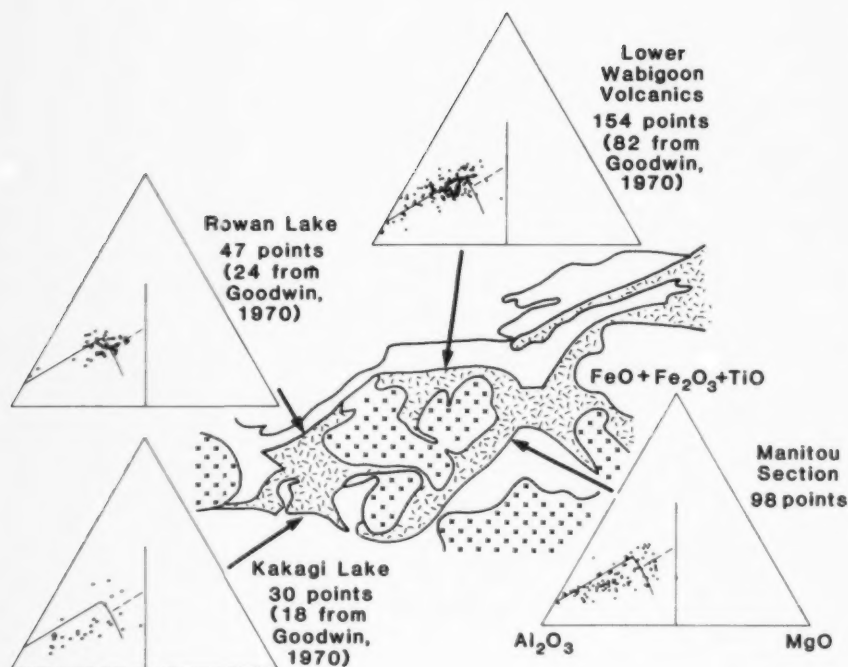
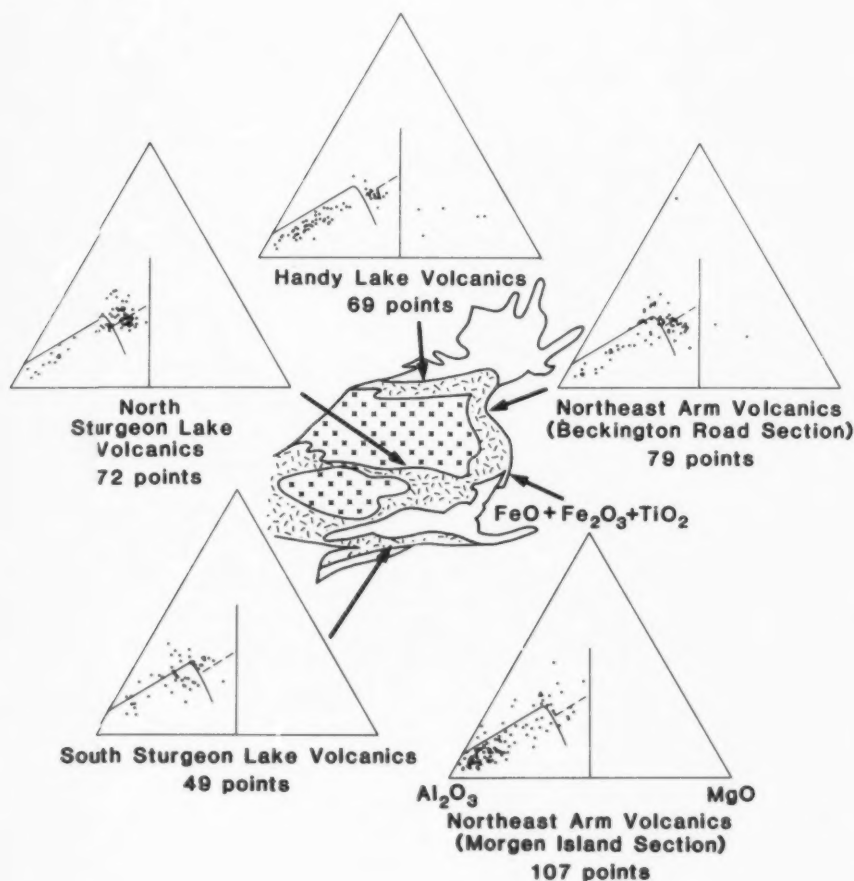


Figure 3.5. Jensen cation plots for Rowan Lake volcanics, Kakagi Lake volcanics, Lower Wabigoon volcanics, Manitou Lakes section, North and South Sturgeon Lake volcanics, and Beckington Road and Morgan Island sections of the Northeast Arm volcanics showing their calc-alkalic to tholeiitic character (from Trowell, Blackburn, and Edwards 1980).



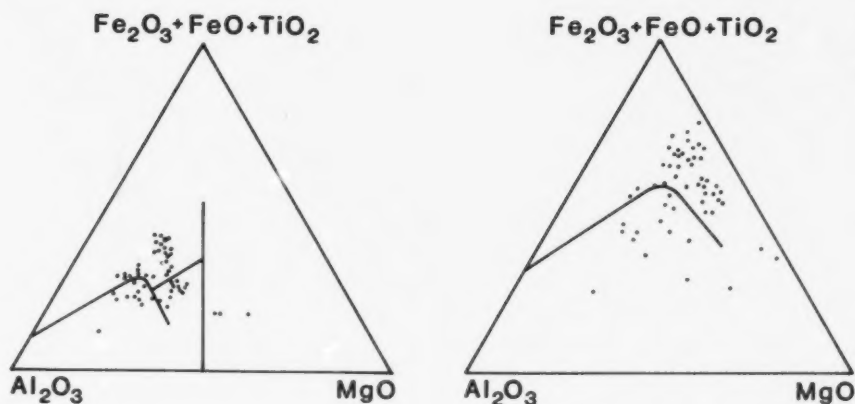


Figure 3.6. Jensen cation and AFM plots of recent data from the Central Volcanic Belt, Sioux Lookout area (from Trowell et al. 1983).

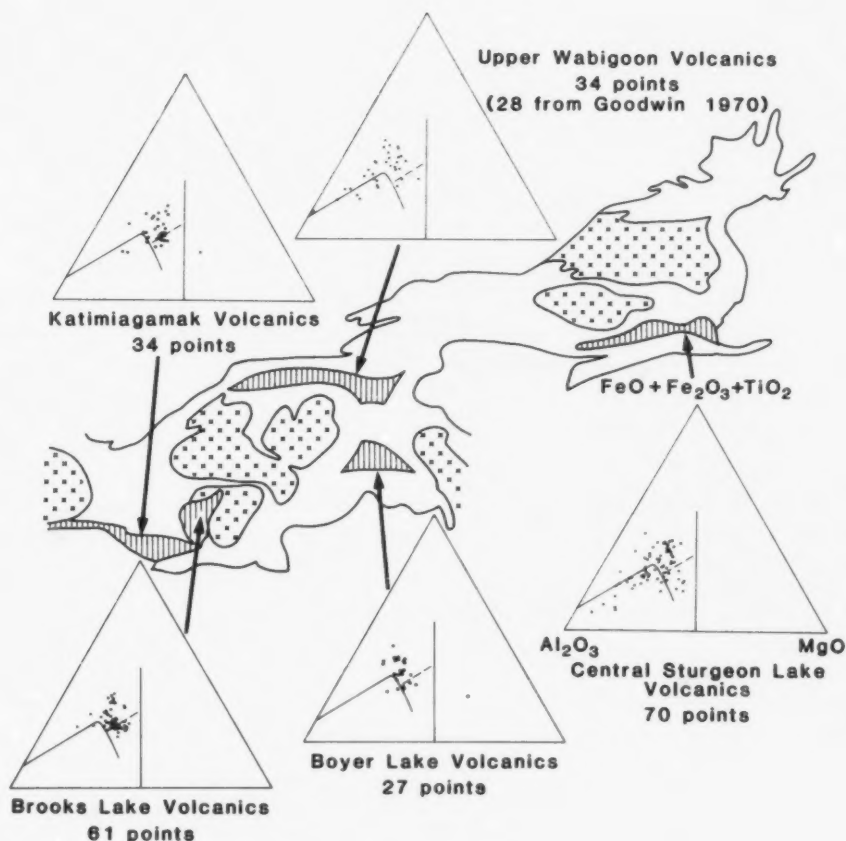


Figure 3.7. Jensen cation plots for Brooks Lake volcanics, Katimigamak volcanics, Boyer Lake volcanics, Upper Wabigoon volcanics, and Central Sturgeon Lake volcanics, showing their tholeiitic, relatively Fe-rich character (from Trowell, Blackburn, and Edwards 1980).

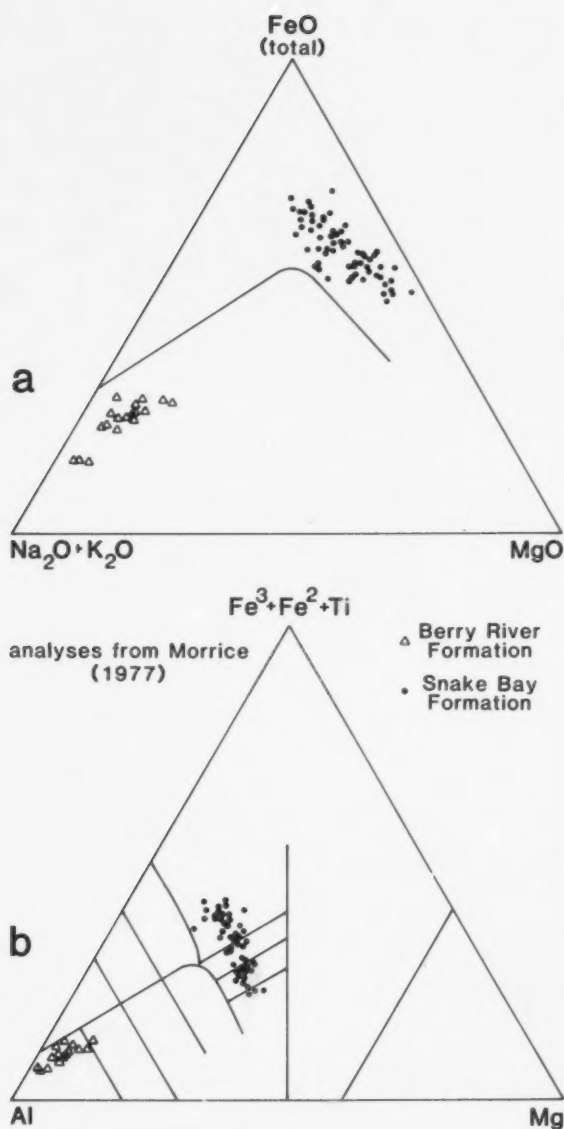


Figure 3.8. Jensen cation and AFM plots of the Berry Creek Complex and Warclub group, and Snake Bay formation (analyses from Morrice 1977).

sequences have been dated mainly because of the lack of zircon-bearing phases in them, so the total time span of volcanism represented in the study area is still unknown. Future uranium-lead zircon dating programs and the use of new dating techniques should resolve this problem. One of the youngest volcanic sequence so far dated is the Berry River formation situated in eastern part of the Lake of the Woods area. Age dating in the Lake of the Woods area proper will determine whether or not the apparent younging of volcanic sequences from Savant Lake southwest to Kakagi Lake is in fact a valid interpretation.

STRATIGRAPHY AND GOLD MINERALIZATION

A brief discussion of mineral deposits in the study area was published previously (Trowell, Blackburn, and Edwards 1980). Since that time, however, there has been renewed interest in gold exploration. For example, the Goldlund Deposit, southwest of Sioux Lookout, is at present being mined; a new gold occurrence has been discovered by Steep Rock Mines Limited at Sturgeon Lake, and numerous other known occurrences or past producers such as the St. Anthony Mine at Sturgeon Lake are being re-examined.

In a previous publication (Trowell, Blackburn, and Edwards 1980), it was suggested that three broad categories of gold occurrences can be recognized in the area: 1) those related to volcanic and subvolcanic stratigraphy, 2) those occurrences associated with later felsic intrusions cutting the volcanic stratigraphy, and 3) occurrences situated within quartz veins having, as yet, no apparent relationship to volcanic activity or igneous intrusions. These categories were defined on the basis of lithologic control, and were not meant to imply genetic relationships, or to rule out the importance of structural control in the localization of gold deposits. Additional categories that could be added include gold occurrences in carbonated, commonly silicified shear zones (for example, Cameron Lake), and gold occurrences situated in mafic volcanic rocks at the greenschist amphibolite metamorphic facies interface.

A guide to areas of gold potential could be the recognition of favourable "packages" of lithologies. For example at Armit Lake west of Savant Lake, the following lithologies are present: mafic volcanic rocks, carbonatized ultramafic rocks (one komatiitic flow), chert magnetite-iron silicate sulphide iron formation and intermediate to felsic tuffaceous rocks. These lithologies suggest active volcanism, with quiescent periods when deposition of iron formation and outpourings of mafic and ultramafic lava occurred; an environment which could be considered to be favourable for gold mineralization.

In the Long Bay-Lobstick Bay area, gold occurs in silicified-carbonatized shear zones, feldspar porphyry, and granitoid stocks. Probably the association having the most economic potential is that of the silicified carbonatized shear zones within mafic metavolcanics. The most extensive shear zone is the Pipestone-Cameron Fault. Within the Long Bay-Lobstick Bay area a significant gold occurrence is found within this fault zone between Regina Bay and Reed Narrows. Here, the Wabigoon Fault and the

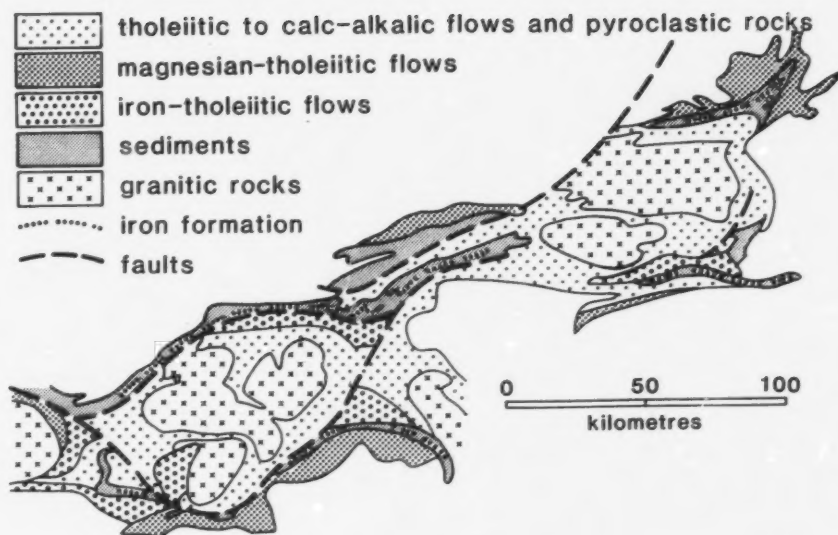


Figure 3.9. Sketch map to show distribution of the three volcanic suites in the study area.

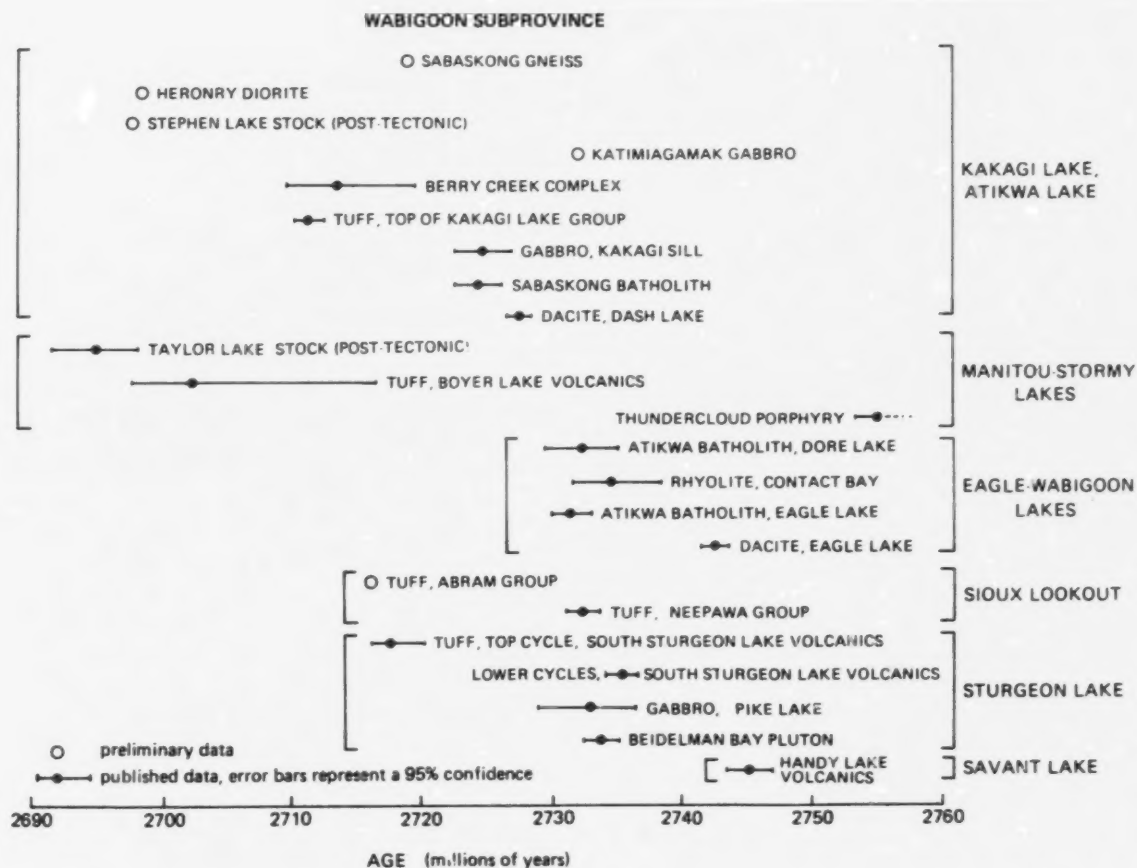


Figure 3.10. Zircon uranium-lead geochronology for Savant Lake-Crow Lake Area.

Pipestone-Cameron Fault merge. Between Hope Lake and the Kishquabik Lake Stock, recent discoveries of gold have been made in smaller quartz-carbonate shear zones cutting the Populus volcanics. Gold has also been noted near feldspar porphyries within the Berry River formation and the Populus volcanics.

The Regina Bay Stock is a tonalite body intruding the Snake Bay formation. A past producer, the Regina Mine, is situated on the south contact of the stock with the mafic metavolcanics where auriferous quartz veins cross the contact. There is potential for additional occurrences in similar situations.

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Chapter 4

Stratigraphic Correlation in the Wawa Area

R.P. Sage

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ABSTRACT

Strike-slip faulting and subsequent folding followed by northwest left-lateral faulting created an unusually complex structural pattern in the supracrustal rocks of the Wawa area, Ontario. Stratigraphic correlation between faulted parts of the supracrustal sequence can be made based on the recognition of repeated systematic compositional variation in the lithologic package, facing directions, and a regionally continuous band of iron formation. Rapid lithologic variation in primary volcanic textures prevents correlation within lithologic sections of similar composition.

Both gold and base-metal mineralization occur within the first of four cycles of volcanism. Gold mineralization is exclusively associated with the fourth cycle of volcanism. Most known gold occurrences which are located at roughly the same general position in the volcanic stratigraphy occur within the thermal aureoles of granitic stocks, or within shallow-dipping shear zones or reverse faults displaying carbonate and silica alteration. Except for a mafic to ultramafic stock which hosts disseminated copper and nickel mineralization, most base-metal occurrences are quartz veins containing minor concentrations of base-metal sulphides.

Ontario Geological Survey mapping continues to delineate areas of economic interest within the first cycle volcanic rocks and to assess the economic potential of later cycles of volcanism. An enhanced understanding of stratigraphy in the supracrustal rocks of the Wawa area will aid in the search for additional deposits of gold and base metals.

INTRODUCTION

In 1979, the Ontario Geological Survey undertook a program to map the main part of the structurally complex Wawa supracrustal belt (Figure 4.1). Thus far, six townships, totalling 560 km², have been completely mapped and mapping in parts of five others has begun. Reports on this work are in preparation.

Before commencing mapping in 1979, examination of previous work indicated a structurally complex belt with a broad range of lithologies. In recognition of the structural complexity, emphasis has been placed on unravelling the framework of the supracrustal sequences. Considerable time and effort has been expended in determining facing directions within supracrustal sections, and in tracing fault zones that subdivide the supracrustals into numerous blocks. Mapping of this complex supracrustal package is continuing.

GENERAL GEOLOGY

The Wawa supracrustal sequence consists of three and possibly four cycles of volcanic rocks. Most of the present mapping has been concentrated in the first or oldest cycle of volcanism which is a north-facing mafic-felsic sequence bounded beneath by

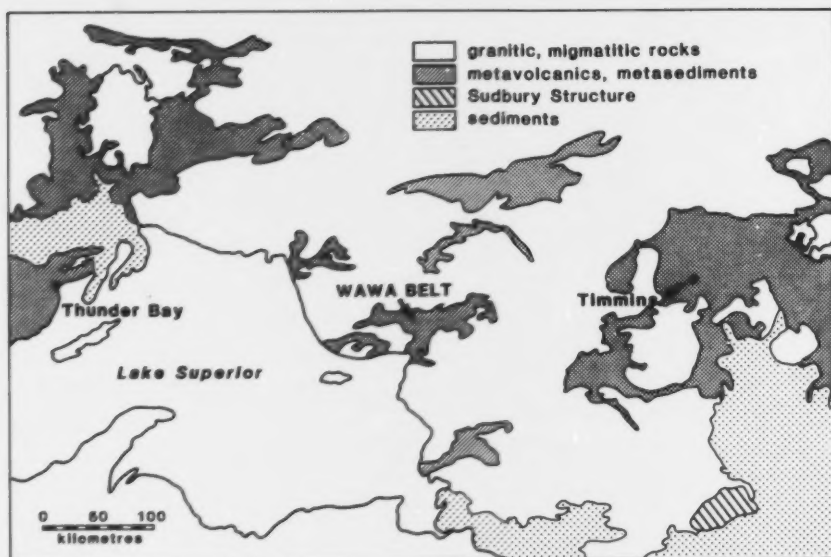


Figure 4.1. Sketch map showing location of the Wawa supracrustal belt.

the external granitic terrain and overlain by the laterally extensive Michipicoten iron formation. Within the lower mafic part of the first cycle, a discontinuous sequence of intermediate to felsic volcanic rocks locally capped with minor iron formation defines an internal subcycle.

Overlying the Michipicoten iron formation and lying beneath clastic sedimentary rocks is approximately 1000 m of intermediate to mafic volcanic rocks which defines part of second cycle volcanism. The clastic sediments consist of wacke, siltstone, argillite, and conglomerate. These sediments are most likely the detritus from the intermediate to felsic volcanic rocks representing the upper part of second cycle volcanism. A volcanic centre associated with second cycle volcanism is represented by the rocks north of the Magpie River. Lateral correlation of the sedimentary and volcanic rocks is difficult due to faulting and folding (Figure 4.2). Within incompletely mapped townships in the north-central part of the belt, the clastic sedimentary rocks are overlain by intermediate to mafic volcanic rocks which may define a third cycle of volcanism.

South of Wawa, a caldera-like structure, defined by the quartz diorite to granodiorite Jubilee Stock enclosed in a partial ring of quartz-feldspar porphyry, may represent a fourth cycle of volcanism (Sage 1979). Correlation of lithologic units across Wawa Lake is difficult due to strike-slip faulting and possible folding beneath Wawa Lake.

The supracrustal sequence at Wawa has been subjected to strike-slip faulting, minor reverse faulting, and intense folding. The folding has become recumbent, and in some areas of the belt such as in Chabanel and Musquash Townships, the stratigraphy is overturned.

After strike-slip faulting and folding, the supracrustal sequence was broken into fault blocks by a series of northwest-trending left-lateral faults. These northwest-trending faults have been intruded by dia-

base dikes, and minor post-dike deformation is locally recognizable. In Late Proterozoic time, a carbonatite complex was emplaced within the Archean supracrustal rocks east of the town of Wawa (Figure 4.2). Numerous lamprophyre dikes which cut the Wawa supracrustal rocks are probably the same age as the carbonatite intrusion.

The structural complexity of the belt and the broad spectrum of rock types present have made it very difficult to unravel its structural and stratigraphic relationships with certainty.

CORRELATION TECHNIQUES

Correlation between various fault-bounded lithologic packages is difficult because of extensive strike-slip and left-lateral faulting and folding. An iron formation unit has proven the most reliable lithologic marker horizon (Figure 4.2). The individual fault segments are named after the segment of iron formation contained within each faulted block: that is, the Lucy iron range, Eleanor iron range, and Josephine-Bartlett iron range.

No single method of correlation by itself has proven satisfactory in further refining the volcanic stratigraphy of the area. Structure and stratigraphy must be used together to unravel the framework of the belt. Marker horizons are absent within the mafic and felsic volcanic sections. Few texturally distinctive lithologic units are present, this inhibits correlation over short distances.

Lithologic correlation can be best made on the basis of rock composition rather than physical features such as varioles, pumice, clast size or shape, or pillow morphology. Major lithological contacts are placed at rock compositional breaks which are not necessarily time equivalent. Recognition of major compositional breaks in combination with bedding and facing attitudes permit correlation within and between fault blocks.

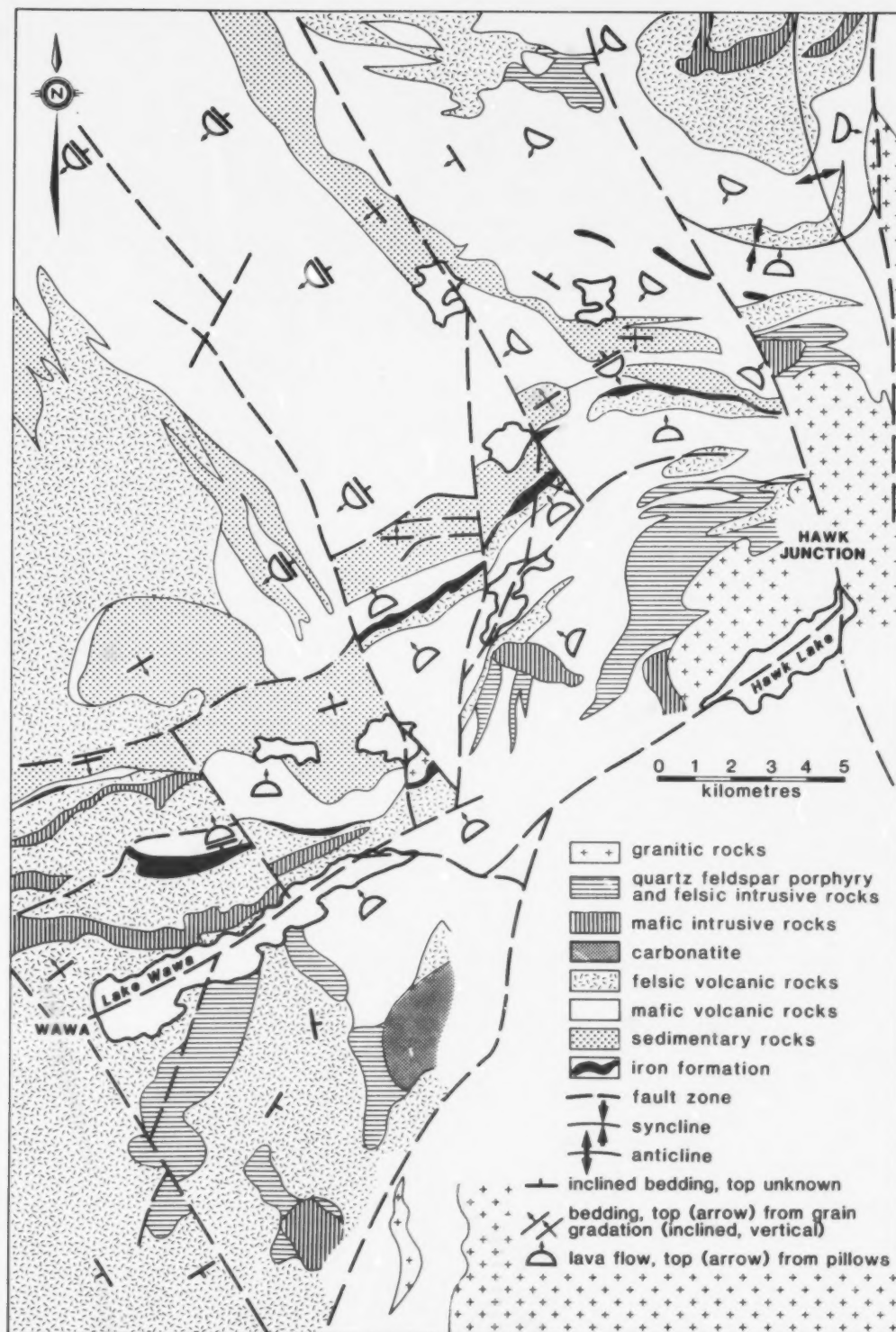


Figure 4.2. Generalized geologic sketch map of mapped area of Wawa supracrustal belt.

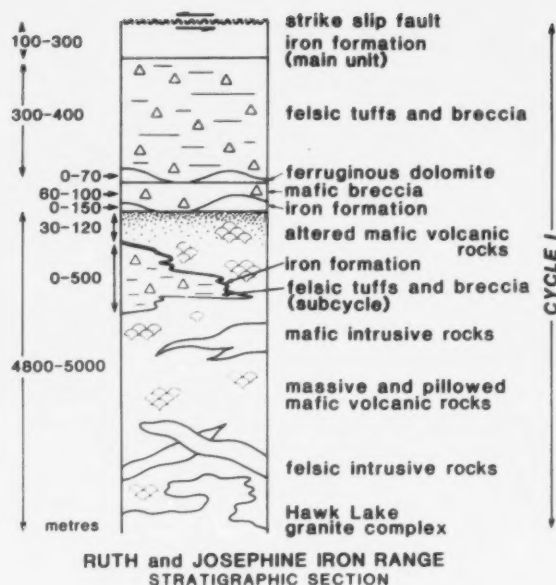


Figure 4.3. Idealized composite stratigraphic section for the Ruth and Josephine iron ranges. Note the stratigraphic position of the ferruginous dolomite and mafic breccia.

The Michipicoten iron formation represents a period of chemical clastic sedimentation during a hiatus between first and second cycle volcanism.

Within the central mafic part of the oldest cycle, a discontinuous zone of felsic volcanic rocks defines an internal subcycle (Figure 4.3) which is locally capped with iron formation. The felsic volcanic rocks of the subcycle consist of tuffs, lapilli-tuffs, quartz-feldspar-phyric crystal tuffs, and minor amounts of breccia. The iron formation of the subcycle consists of a lower sulphide and upper chert member and is narrower and more discontinuous than the iron formation that caps the major cycle. Carbonate facies (that is, siderite) have not been observed in this iron formation, and the chert-magnetite and graphite-argillite facies are either absent or poorly developed. Carbonate facies iron formation has been reported to be present in the Kathleen iron range which is part of the internal cycle (Assessment Files Research Office, Ontario Geological Survey, Toronto (AFRO)).

By contrast, within the Michipicoten iron formation, a consistent facies variation has proven to be a reliable facing indicator. From bottom to top, the commonly observed sequence is siderite, pyrite, chert-magnetite-wacke, chert-wacke, and argillite-pyrite (Figure 4.4). One or more of these facies may be absent in any given area, but where two or more are present, facing direction can be determined.

A mafic breccia at the top of the intermediate to mafic part of the oldest cycle and a ferruginous dolomite stratigraphically above the breccia have proven to be reliable local marker horizons beneath the Lucy, Ruth, and Josephine-Bartlett iron ranges (see Figure 4.3). Mapping has disclosed numerous

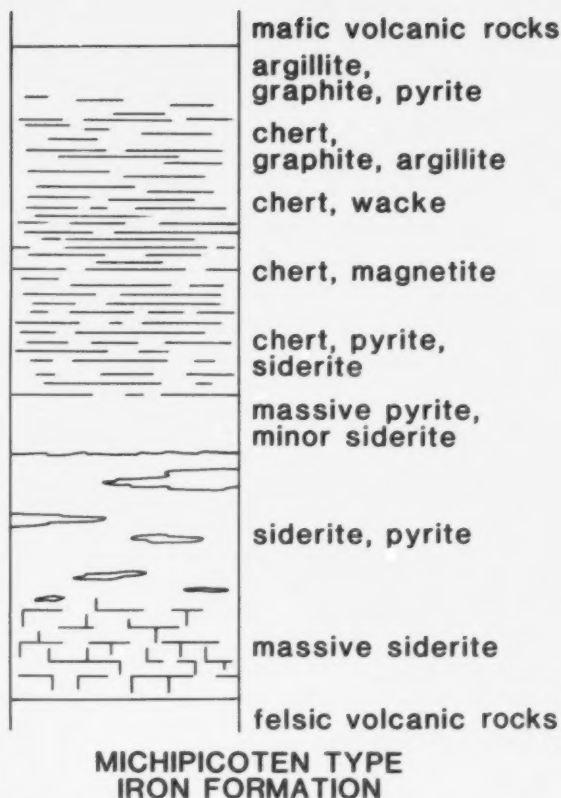


Figure 4.4. Idealized schematic of facies in Michipicoten iron formation. Note sharp upper and lower contacts and gradational internal contacts.

magnetite-bearing flows in the mafic part of the early cycle and these could be used as geophysical marker horizons.

The mafic breccia likely consists of more than one flow unit and contains considerable carbonate. The clasts are rounded to angular and more felsic than the dark green to black matrix. They commonly display both a reaction rim and an accretionary rim up to 4 to 6 mm thick. The breccia unit, which displays crude bedding and poor sorting, is locally polymictic containing iron formation and sulphide clasts in addition to felsic volcanic clasts, some of which are vesicular and pumiceous.

The ferruginous dolomite associated with the mafic breccia is fine grained, massive, and rusty weathered, with a thinly bedded base. The unit commonly displays a random criss-crossing pattern of milky quartz stringers. The criss-crossing stringers of quartz and rusty weathering make this unit easily recognizable in the field.

The volcanic rocks of the oldest cycle consist of a lower sequence of massive to pillowed volcanic rocks of iron tholeiite composition (Figure 4.5). The overlying felsic volcanic rocks consist of tuff, lapilli-tuff, feldspar phyric crystal tuff, quartz-feldspar-

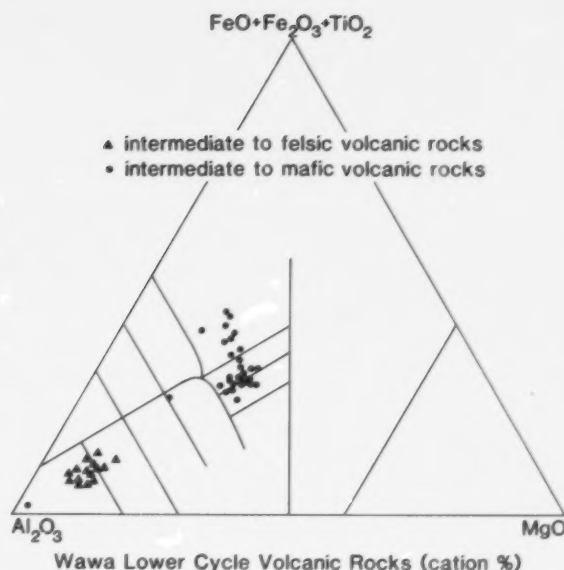


Figure 4.5. Jensen cation diagram of oldest cycle volcanic rocks. Note strongly bimodal character and high-iron tholeiitic nature of mafic volcanic rocks.

phyric crystal tuff, spherulitic flows, and coarse breccias of rhyolite to dacite composition. The calc-alkalic and tholeiitic parts of the oldest cycle are compositionally strongly bimodal, implying no simple direct petrogenetic relationship (Figure 4.5).

The mafic and felsic volcanic rocks of the second cycle display primary structures similar to first cycle rocks and are indistinguishable in the field from first cycle volcanic rocks on the basis of appearance.

The Hawk Lake granitic complex, which contains inclusions of the mafic part of the oldest cycle, has been dated by uranium-lead zircon techniques as 2888 ± 2 Ma (Turek 1983), and felsic tuffs immediately below the Michipicoten iron formation at the Helen iron range have been dated by uranium-lead techniques as 2749 ± 2 Ma (Turek *et al.* 1982). Hence, on the basis of these isotopic ages, the development of the oldest cycle exceeds 130 Ma. The felsic volcanic rocks of the second cycle have been dated by uranium-lead techniques as 2696 ± 2 Ma (Turek *et al.* 1982).

Within the area mapped to the present, most mineralization occurs in the oldest cycle (Figure 4.6). Gold mineralization, by itself without any other associated economic mineralization, occurs in association with the epiclastic tuffs of Cycle Four that have been intruded by the Jubilee Stock.

On the basis of records on file in the Assessment Files Research Office, Ontario Geological Survey, Toronto, anomalous levels of copper and gold occur in a minor iron formation unit overlying felsic volcanic rocks within the mafic part of the oldest cycle. Surface samples collected during the present survey

have not yet fully confirmed these reports of anomalous copper and gold.

The value of the Michipicoten iron formation is its iron content only. Geochemically anomalous values of copper, nickel, gold, and zinc have been reported (Assessment Files Research Office, Ontario Geological Survey, Toronto; Collins and Quirke 1926; Richter 1952) but again, surface sampling during the recent mapping has not indicated anomalous base- or precious-metal contents.

The gold showings in the southeastern part of the region (Figure 4.6) are in most cases quartz veins associated with shearing and carbonatization at lithologic contacts. These showings appear to occur regionally where metamorphic grade is transitional from greenschist to lower amphibolite. This transition is recognized in the field by decreasing carbonate content and the appearance of amphibole. The amphibole has been altered to chlorite suggesting that it has undergone retrograde metamorphism.

The same gold showings all occur at approximately the same distance from the contact of the Hawk Lake granitic complex and may be related to the thermal aureole of that complex. The possibility, therefore, exists that 1 or more lithologic units once contained gold that has been remobilized and concentrated into veins or shear zones.

Base-metal showings are nearly all sulphide-bearing quartz veins of limited extent, and are restricted to the lower part of the oldest cycle. The most significant base-metal mineralization in the mapped part of the belt involves disseminated copper and nickel sulphides with platinum values in a mafic intrusion cutting volcanic rocks of the oldest cycle. This body sharply crosscuts lithologic trends. Immediately south of the disseminated copper and nickel occurrence, a massive sulphide showing, 1 m in width, occurs along a contact between mafic volcanic rocks and a quartz porphyry intrusive rock. Based on diamond drilling, this high grade copper, zinc, and silver occurrence does not appear to be traceable laterally or to depth.

A high grade silver, lead, and lead-bearing quartz vein is the only mineralization found in the felsic part of the oldest cycle and in fact, occurs in a quartz diorite intrusion cutting the volcanic rocks. This showing lies below the Helen iron formation and appears to be quite small. Grab samples from this vein exceed 40 ounces silver per ton.

South of Wawa, an area of gold mineralization may be associated with the thermal aureole around the Jubilee Granitic Stock which appears to be centred within a caldera structure (Sage 1979; Figure 4.6). The central stock is of dioritic to granodioritic composition, contains numerous blocks of volcanic rocks, and locally displays an intrusive breccia margin. The stock is exposed at a structurally high level. An outer ring fracture is occupied by massive quartz-feldspar porphyry that partly encloses the stock. The gold commonly occurs within quartz lenses that cut and are concordant with redeposited tuffaceous units of andesitic to dacitic composition, marginal to the granitic stock. These epiclastic tuffs are tentatively interpreted to represent the fourth cycle of volcanism in the Wawa area. Bedding in the tuffs dips away

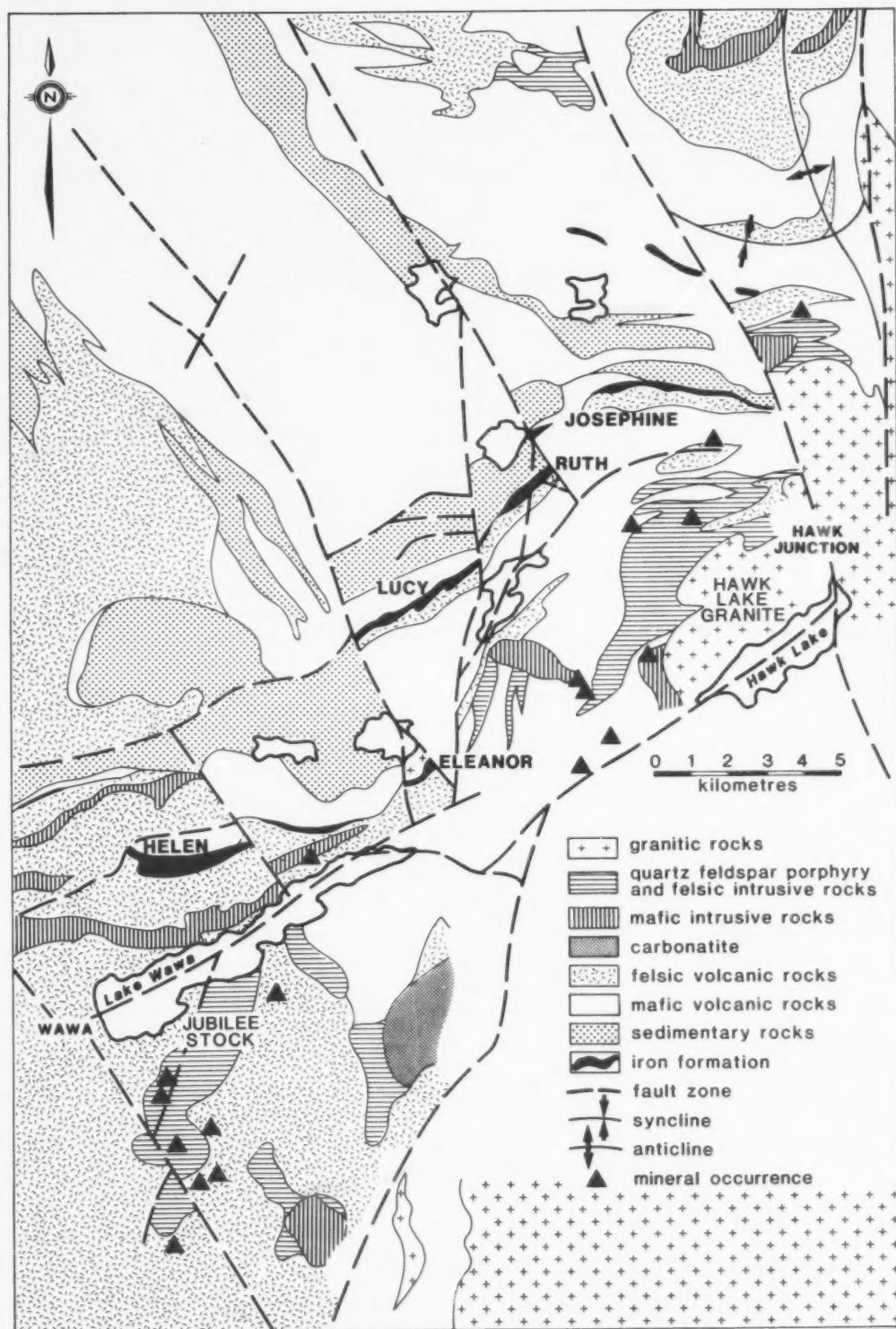


Figure 4.6. Geologic sketch map of oldest cycle volcanic rocks with more prominent mineral occurrences and former producing mines.

from the stock and strikes parallel to the volcanic - plutonic contact. Lensoid in plan view, these lithologic units occupy former topographic depressions on the flanks of the former volcano and represent rapid subaqueous deposition of volcanic detritus from the volcanic edifice which existed above the Jubilee Stock.

Early studies of the gold deposits south of Wawa classified the deposits as quartz veins (Frohberg 1937; Gledhill 1927). These investigators recognized at least two ages of veining. The gold mineralization was said to be associated with the older quartz veins that display a sugary texture and contain minor concentrations of sulphide, principally pyrite and chalcopyrite. Later, coarsely crystalline quartz veins were described as barren with respect to gold and are deficient in sulphides (Gledhill 1927; Frohberg 1935). Samples of coarsely crystalline barren quartz vein material collected during recent mapping generally confirmed these observations.

Recently, a re-evaluation of several gold deposits south of Wawa has been completed by Dunraine Mines Limited under the direction of Mr. G. Harper and Dr. P. Studemeister, Consulting Geologists. At least some of the gold-bearing veins are presently referred to as lenses and are interpreted to be sugary quartzites, or in some cases, recrystallized cherty tuffs deposited within a sequence of redeposited tuffs on the flanks of a former volcano (H. Koza, Dunraine Mines Limited, personal communication, 1983). The lenses are limited in exposure and lack internal bedding and contain volcanoclastic fragments. The gold deposits are considered to have formed either as subaqueous placers or as redeposited gold-bearing cherty tuffs. This interpretation is based on the presence of tuffs displaying good primary sedimentary structures above and below the Parkhill gold-bearing lenses, the crudely conformable nature of some lenses, and the presence of gold-bearing siliceous tuff lenses within the epiclastic tuffs. Outlines of underground stopes on existing mine plans suggest the possibility that meandering streams may have influenced gold distribution. If this model is correct, the source beds proximal to the volcanic vent have likely been removed by erosion of the former volcanic edifice above the Jubilee Stock, however, the location of allochthonous deposits of economic significance may be possible.

Gold also occurs as lensoid quartz bodies within altered early shear zones. These zones possibly represent reverse faults that cut the Jubilee Stock. The nature of these quartz lenses is uncertain and some could be siliceous mineralized tuffs incorporated into the faults. The reverse faults and strike-slip faults are the oldest recognized faults in the Wawa area and are offset by northwest-trending left-lateral faults. In addition to silicification, the shear zones are carbonated and contain minor disseminated pyrite.

CONCLUSIONS

In summary, geologic mapping in the Wawa area so far has shown that major gold and base-metal mineralization is largely restricted to one major mafic-felsic volcanic cycle and that a period of solely gold mineralization occurs in the latest cycle of volcanism. Most base-metal occurrences are restricted to a broad zone that parallels stratigraphy. Gold mineralization occurs in discrete lithologic units, in a broad zone that is parallel to lithologic trends, and in the thermal aureoles of granitic intrusions. Gold also occurs in early reverse faults in association with silicification and carbonatization.

Due to the complex structure of the Wawa supra-crustal belt, much time consuming detailed mapping is required to unravel the structure and stratigraphy and to trace zones of economic interest. Plans for the future are to continue mapping lower cycle volcanic rocks and to complete additional mapping and economic evaluation of the volcanic rocks of the later cycles. The mapping program will ultimately provide the data base to permit identification of areas of greatest mineral potential.

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Chapter 5

Mineralization and Volcanic Stratigraphy in the Western Part of the Abitibi Subprovince

L.S. Jensen

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ABSTRACT

The distribution of mineralization in the western part of the Archean Abitibi Subprovince is closely related to the volcanic sedimentary stratigraphy of the subprovince. Supergroups composed of komatiitic, tholeiitic, calc-alkalic, and alkalic volcanic groups developed during cycles of volcanism. Separate supergroups can be recognized in different parts of the area. Mineralization repeatedly occurs in the same lithologies at the same stratigraphic position in each of the supergroups. Massive copper-lead-zinc deposits, Iron Formation, and stratiform gold mineralization occur in the calc-alkalic phases of at least two supergroups. Massive nickel deposits, and asbestos, magnesite, and talc deposits are associated with the komatiitic flows and related intrusions. Lode gold deposits are concentrated near the Kirkland Lake-Larder Lake and Destor Porcupine Fault Zones and are associated with late alkalic volcanism and intrusions of the youngest supergroup.

A knowledge of regional stratigraphy and structure in combination with a geological model of greenstone belt development allows interpretation of environments favourable for mineral deposit formation. The megacauldron model suggests that base-metal sulphide deposits, iron formations, and stratiform gold mineralization are preferentially located in the central vent area, shelf, and outer shelf margins of a mature calc-alkalic pile, respectively. Nickel mineralization occurs where komatiitic lavas onlap rocks of an older calc-alkalic pile, whereas asbestos, talc, and magnesite occur in peridotitic sills with olivine-rich cumulates which have been penetrated by hydrous fluids. Lode Gold deposits appear to be associated with felsic intrusive and extrusive rocks in areas where stratiform gold-bearing sedimentary rocks may have been deposited and buried by younger mafic volcanic rocks.

INTRODUCTION

This chapter examines the general relationship between various types of mineralization and volcanic stratigraphy in the western part of the Archean Abitibi Subprovince of the Canadian Shield (Figure 5.1). Six principal types of mineralization occur in this part of the Abitibi Subprovince (Table 5.1). Numerous authors have long recognized the close spatial association between specific kinds of mineralization and certain volcanic, sedimentary, and intrusive rock types within mining camps (Goodwin 1965; Hutchinson 1973; Pyke 1976). However, attempts to interrelate mining camps have met with limited success (Colvine *et al.* 1984). Only recently has sufficient information become available about the volcanic stratigraphy in this region to permit discussion of the relationship between mineral deposits in the various mining camps and the overall volcanic stratigraphy.

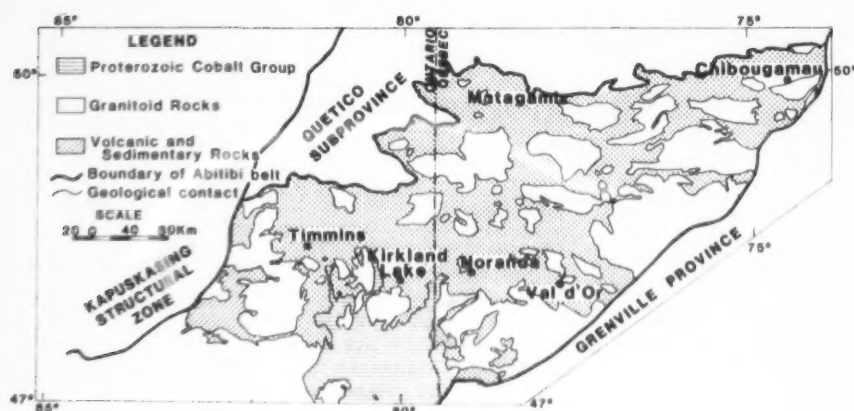


Figure 5.1. Map of the Abitibi Subprovince.

TABLE 5.1: TYPES OF MINERALIZATION OCCURRING IN THE WESTERN PART OF THE ABITIBI SUBPROVINCE.

MINERALIZATION	ASSOCIATED ROCK TYPES
1. Massive Cu-Zn-Pb Deposits	Proximal and central vent calc-alkalic volcanic rocks
2. Iron Ore Deposits	Distal calc-alkalic felsic tuffs, turbidic sedimentary rocks $\pm$ mafic and ultramafic volcanic rocks
3. Stratiform Gold Deposits	Turbiditic and chemical sedimentary rocks $\pm$ mafic and ultramafic volcanic rocks
4. Massive Ni-Cu Deposits	Ultramafic volcanic rocks $\pm$ turbiditic sedimentary rocks and calc-alkalic felsic tuffs
5. Asbestos, Magnesite, and Talc Deposits	Ultramafic intrusive and extrusive rocks
6. Lode Gold Deposits	Alkalic felsic intrusive and extrusive rocks

Numerous petrogenetic theories and models have been proposed to explain the types of mineralization listed in Table 5.1. No single model adequately explains all the features which are associated with any of these types of mineralization. In this paper, brief reference will be made to various models as they relate to the volcanic stratigraphy. No exhaustive attempt will be made to prove or disprove any particular model; instead, the aim will be to identify the stratigraphic environment in which particular types of mineralization tend to occur, and to

suggest where in the western part of the Abitibi Subprovince similar mineralization could be present.

Volcanic stratigraphy can be an important guide for mineral exploration, both on regional and local scales. On a local scale, volcanic stratigraphy has played an important role in locating additional mineralization in many of the mining camps and will be increasingly important as Archean volcanism and crustal development becomes better understood.

On a regional scale, volcanic stratigraphy serves several purposes in the field of mineral exploration. It provides an essential panoramic view of the variety of rocks and their distribution, which gives insight into patterns of Archean volcanism, sedimentation, and plutonism in a given greenstone belt. This information, when applied to more general models of Archean greenstone belt development, helps in the recognition of favourable environments for mineral deposit formation by comparing existing Archean deposits with more recent examples of mineralization. As well, the distinctive types of mineralization found in widely separated mining camps within a greenstone belt can be put in perspective.

Jensen (1981a) and Jensen and Langford (1985) proposed that the rocks of the western part of the Abitibi Subprovince were formed by a series of megacauldrons originating above mantle diapirs. This model can be applied to explain the volcanic stratigraphy, structural features, and metamorphism found in this part of the subprovince. It is the author's opinion that folding and faulting were contemporaneous with volcanic activity and exerted control on the volcanic stratigraphy and environments favourable to particular types of mineralization (Jensen 1981a, 1981b).

REGIONAL STRATIGRAPHY AND STRUCTURE

The volcanic and sedimentary rocks of the Timmins-Kirkland Lake-Noranda part of the Abitibi Subprovince form a large east-trending synclinorium (Figure 5.2). Domal tonalitic to trondhjemitic batholiths and gneissic terrains are present north, south, and west of the central synclinorium. Two major fault zones, the Destor-Porcupine Fault Zone and the Kirkland Lake-Cadillac Fault Zone, transect



Figure 5.2. Geological map of the Timmins-Kirkland Lake area.

the northern and southern limbs of the synclinorium, respectively, and numerous small plutons of granodioritic to syenitic composition cut all the volcanic and sedimentary rocks. Diabase dikes varying from Archean to Late Proterozoic in age occur throughout the area, and Proterozoic sedimentary rocks of the Huronian Supergroup onlap the Archean rocks from the south. Regional metamorphism of the Archean rocks is subgreenschist facies (Jolly 1976, 1978; Gélinas *et al.* 1982).

A regional synthesis of the volcanic stratigraphy of the Abitibi Subprovince has recently been published in Map 2484 (MERQ-OGS 1983). The volcanic rocks form a number of supergroups, which consist of a group of komatiitic flows at the base, overlain in turn by groups of tholeiitic lavas, calc-alkalic volcanic rocks, and in places, alkalic lavas (Figure 5.3).

The various supergroups are shown on Figures 5.4, 5.5, 5.6, and 5.7. They include: the Deloro Group (Pyke 1982) south of Timmins (Figure 5.4), the top of which has been dated at 2725 ± 2 Ma (Nunes and Pyke 1980); the Wabewawa-Catherine-Skead Supergroup south of Kirkland Lake (Figure 5.5), dated at 2710 ± 2 Ma (P.D. Nunes, formerly with Royal Ontario Museum, personal communication, 1982) and the Upper Supergroup shown in Figure 5.6, the upper parts of which have been dated at 2703 ± 2 Ma (Nunes and Jensen 1980). The Upper Supergroup comprises komatiitic flows of the Lower Tisdale Group (Figure 5.4), Larder Lake Group (Figure 5.5), Stoughton-Roquemaure Group (Figure 5.7), and the Malartic Group (Figure 5.6) (MERQ-OGS 1984). These komatiitic successions are overlain by the tholeiitic Kinojevis Group and calc-alkalic Blake River Group

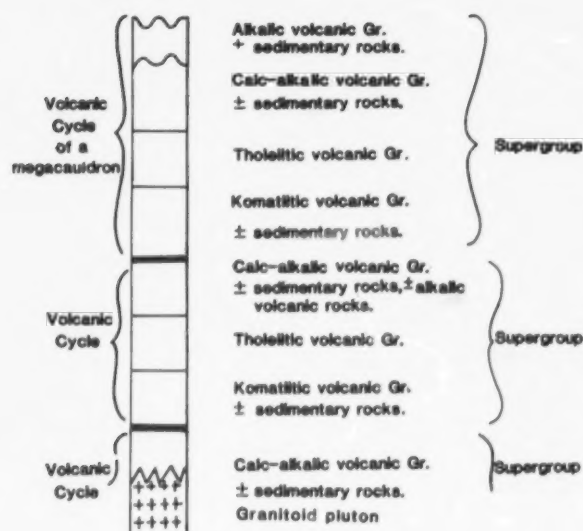


Figure 5.3. Illustration of stratigraphic column resulting from volcanic cycles.

(Figure 5.6). Alkalic flows of the Timiskaming Group unconformably overlie the Kinojevis and Blake River Groups. The apparent stratigraphic thickness of the Wabewawa-Catherine-Skead Supergroup is 16 km and the thickness of the Upper Supergroup is >30 km. The Kidd Creek Rhyolites (2708 ± 2 Ma, Nunes and Pyke 1980), Pacaud Tuffs, and Hunter Mine Group (2710 ± 2 Ma, Nunes and Jensen 1980) are considered to be the upper calc-alkalic parts of less well preserved supergroups (Figures 5.4, 5.5, and 5.7, respectively). Regional correlation of the volcanic stratigraphy is presented in Figure 5.8 and Table 5.2.

PETROGENESIS OF THE WESTERN ABITIBI SUBPROVINCE

Jensen (1981a) and Jensen and Langford (1985) proposed that each supergroup represented a volcanic cycle related to the development of a megacauldron formed above a mantle diapir (Figure 5.9). The first magmas to reach surface formed komatiitic and tholeiitic lavas. As the accumulations of these flows thickened above the diapir, they subsided by downfolding and faulting, particularly in the central parts of the megacauldron. With depth, under increasing pressures and temperatures, the lower core komatiites and tholeiites were transformed into more dense amphibolite, garnet granulite, and eclogite which further promoted subsidence of the overlying rocks. At lower crustal and upper mantle depths, the komatiites and tholeiites which had been partly converted to eclogite began to undergo about 10% partial melting. This resulted in the formation of calc-alkalic magmas which then rose to the surface, producing the observed change from tholeiitic to calc-alkalic volcanism. A thick succession of calc-

alkalic volcanic rock accumulated in the core of the megacauldron as the result of continued subsidence and the simultaneous formation of volcanic edifices. Ultimately, the partial melting of basal calc-alkalic volcanic rocks resulted in formation of trondhjemitic magmas which intruded the cores of the calc-alkalic piles. Distal calcalkalic tuffs and sedimentary rocks were deposited on the margins of these volcanic piles. At depth, the garnet-bearing residuum from the partial melting of the volcanic rocks sank farther into the mantle.

In the older megacauldrons, where the calc-alkalic piles formed sufficiently large masses, the growth of core trondhjemitic rocks resulted in composite batholiths. The low specific gravity of the trondhjemitic rocks caused the rocks near surface at the centres of the megacauldrons to stop subsiding. Instead, the denser marginal volcanic and sedimentary packages subsided by their supporting rocks being drawn downward and inward under the batholith to replace eclogitic rocks sinking below it. At surface, these marginal packages gradually tilted to face away from the actual batholith. Marginal subsidence continued where accumulation of additional komatiitic and tholeiitic rocks from a newly developing megacauldron nearby overlapped the rocks of the older megacauldrons, and resulted in these rocks forming thick outward-facing homoclinal successions. For example, the Round Lake, Lake Abitibi, and Kenogamissi Batholiths were primary megacauldrons (see Figure 5.2). The calc-alkalic volcanic Pacaud Tuffs and Hunter Mine Group are all that remain of the volcanic phases from these primary megacauldrons (Figure 5.5 and 5.7). Succeeding megacauldrons developed east of the Round Lake Batholith to form the east-facing homoclinal Wabewawa-Catherine-Skead Supergroup (Figure 5.10). The Deloro Group, and, north of Timmins, the Kidd Creek Rhyolites (Figure 5.4) were formed east of the Kenogamissi Batholith.

The youngest megacauldron developed in the area is presently occupied by the Central Synclinorium (Figures 5.11 and 5.6). Initial komatiitic flows at the base of the Upper Supergroup lapped onto the rocks at the edges of the older megacauldrons. Where these rocks are still preserved, they serve to outline the youngest megacauldron. As volcanism progressed, subsidence of the central komatiitic and succeeding volcanic rocks occurred in the central part of the megacauldron, largely by downfolding and faulting along the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zone. The location of these two fault zones is believed to approximate the edges of the volcanic-sedimentary piles associated with the earlier megacauldrons. Downfolding and faulting also occurred in the core of the synclinorium during the accumulation of the calc-alkalic Blake River Group (Figure 5.6).

MINERALIZATION

INTRODUCTION

Pyke (1982) concluded that much of the mineralization in the Timmins area occurred near the contact between the felsic volcanics and sedimentary rocks of the older volcanic cycles (Deloro and Porcupine

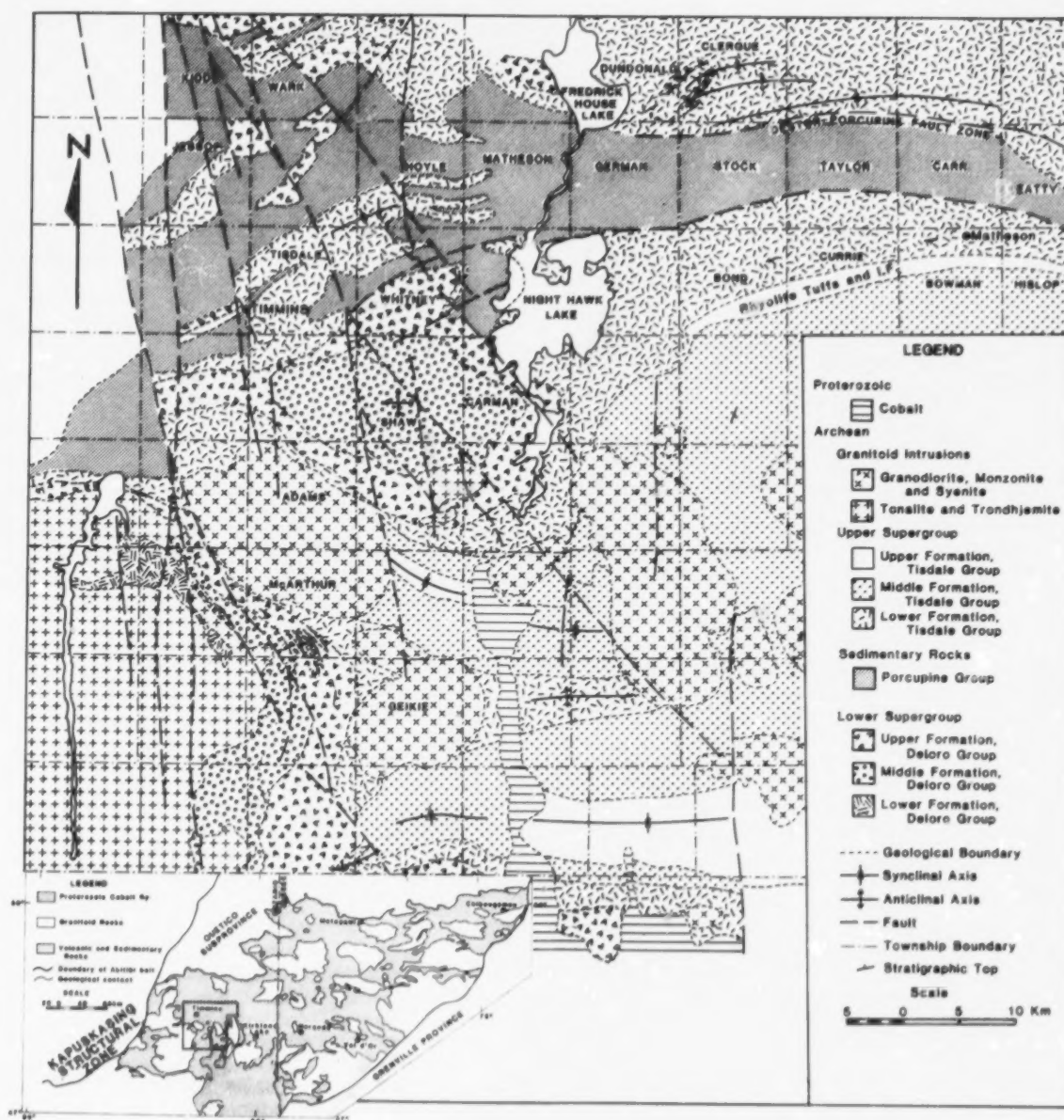


Figure 5.4. Geological map of the Timmins area.

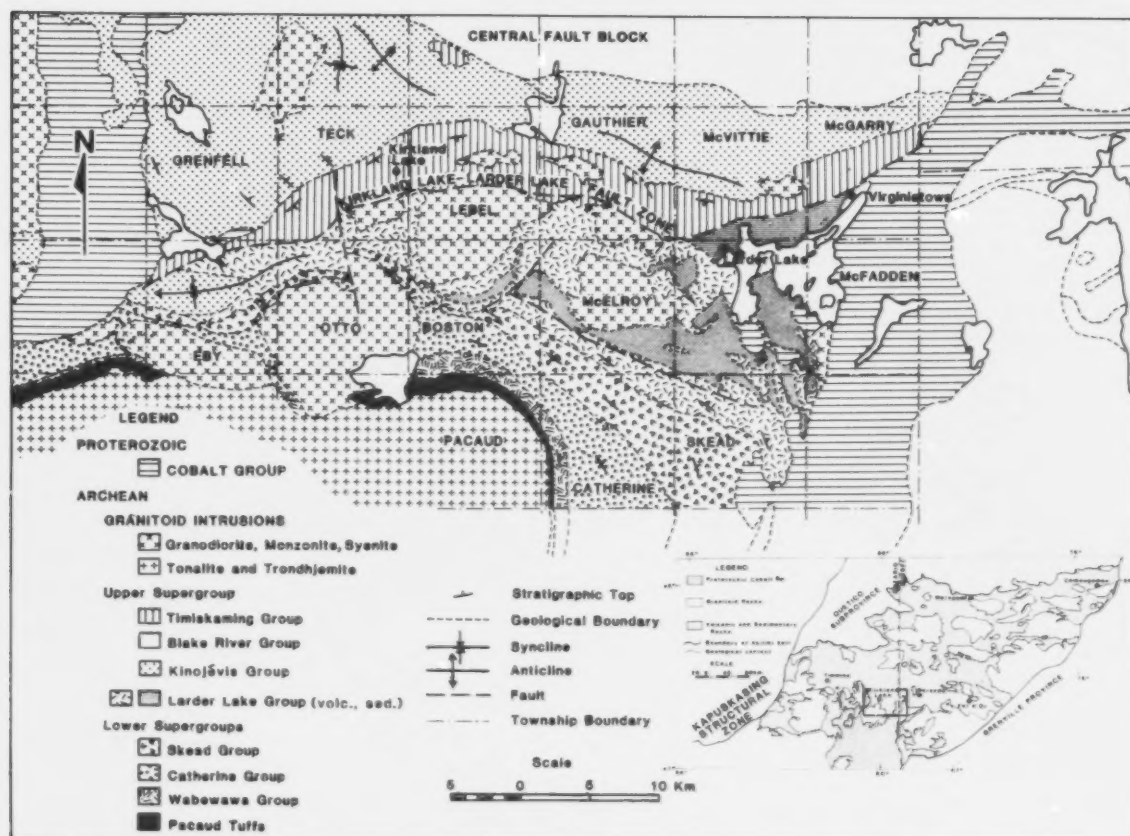


Figure 5.5. Geological map of the Kirkland Lake-Larder Lake area.

Groups) and the komatiitic rocks of the younger volcanic cycle (Tisdale Group) (Figure 5.4). The determination of the significance of this stratigraphic contact is critical to the understanding of interrelationships between the gold, nickel, base-metal, talc, magnesite, asbestos, and iron ore deposits of the Timmins area, as is an assessment of the degree of stratigraphical control of mineralization. It is also important to determine whether or not possible stratigraphic controls also apply in other mining camps in the Abitibi Subprovince.

TECTONO-STRATIGRAPHIC SETTING

Base-metal, iron ore, and stratiform gold deposits appear to have been closely associated with episodes of calc-alkalic volcanism and sedimentation during the development of the megacauldrons. In the calc-alkalic volcanic piles, base-metal deposits are found in the proximal and near vent flows and tuffs. Away from the vent areas, banded iron formation tends to be interbedded with distal tuffs and tuff-breccias interlayered with sedimentary rocks composed of volcanic debris, chert, and in places, carbon and carbonate that likely formed in shelf areas marginal to the calc-alkalic pile. Farther away from

the pile, where the shelves sloped steeply into neighbouring basins, stratiform gold deposits developed in association with deposition of chert, carbonate units, graphite, ironstone, and distal ash tuff. These mineralized sediments tend to be interlayered with turbiditic wacke, mudstone, and conglomerate eroded from the calc-alkalic volcanic pile. In the Abitibi Subprovince, the stratiform gold-bearing sedimentary rocks occur interlayered with komatiitic and tholeiitic flows that were laid down at the onset of volcanism associated with the development of younger megacauldrons in the neighbouring basins. Because of tectonic activity along the shelf-basin interface and the emplacement of komatiitic and tholeiitic magmas, the gold tends to be remobilized into fractures, quartz and carbonate veins, and alteration zones. In this chapter, these types of lode gold deposits are distinguished from lode gold mineralization closely associated with late alkalic extrusive and intrusive rocks.

Massive nickel sulphide deposits and asbestos, magnesite, and talc deposits are associated with the komatiitic volcanic sequences of the megacauldrons. The nickel mineralization is largely concentrated in komatiitic flows that are in contact with sediments,

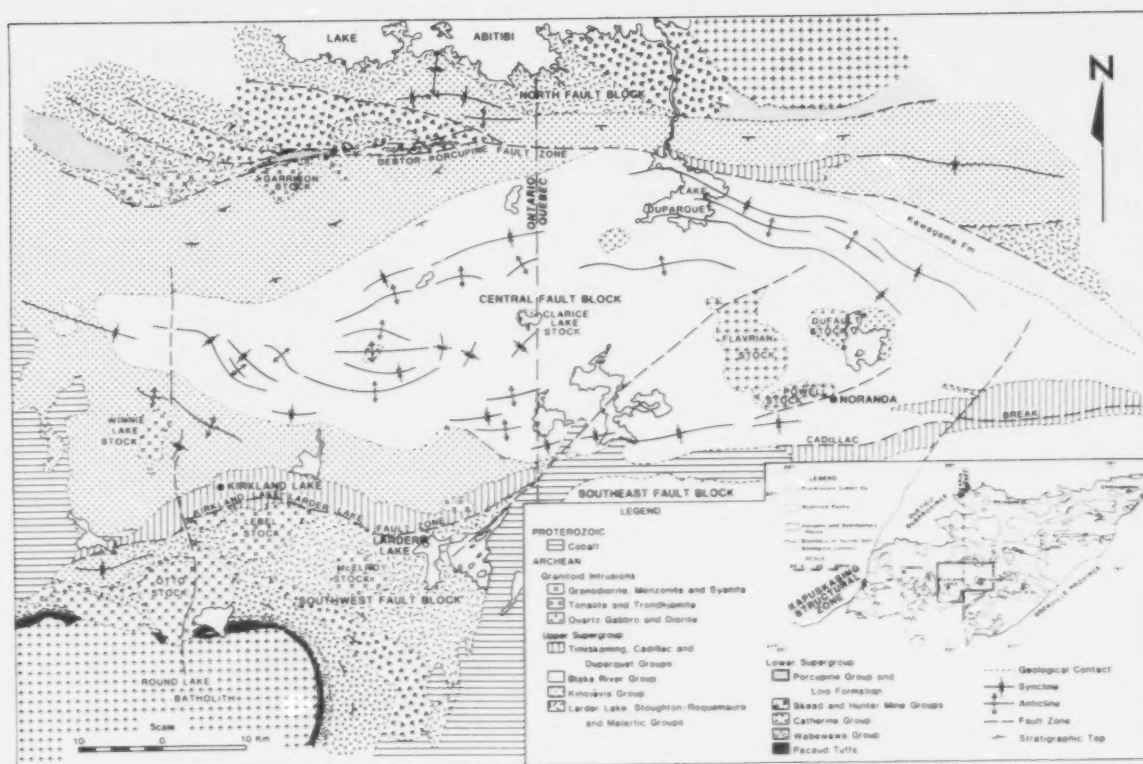


Figure 5.6. Geological map of the Kirkland Lake-Noranda area.

felsic tuffs, iron formation, and calc-alkalic lavas of the preceeding megacauldrons. Asbestos, magnesite, and talc deposits are located in dunitic parts of peridotitic stocks, sills, and thick komatiitic lava flows that are found near the base of the komatiitic succession and intruding the older rocks of the preceeding megacauldron.

Lode gold mineralization is also closely associated with the final magmatic phase of a megacauldron that typically produces alkalic felsic intrusive and extrusive rocks. Gold is epigenetically concentrated in quartz and quartz-carbonate veins, in fracture fillings, in alteration zones and contact metamorphic aureoles, and in the felsic rocks themselves.

MASSIVE COPPER-ZINC-LEAD SULPHIDE DEPOSITS

Massive copper-zinc-lead sulphide deposits are located in the proximal and central vent facies of calc-alkalic volcanic rocks in the Lower Supergroups as well as in the Upper Supergroup formed by successive megacauldrons. In the Upper Supergroup, the main massive sulphide deposits are in the Blake River Group (2703 ± 2 Ma, Nunes and Jensen 1980). In the Lower Supergroup, they are located north of Timmins associated with the Kidd Creek Rhyolites (2708 ± 2 Ma, Nunes and Pyke 1980) (Figure 5.4). In addition, the Normetal Mine, immediately northeast of Lake Abitibi, is situated in calc-alkalic volcanic rocks

(Bertrand and Hutchinson 1973) which maybe part of the Hunter Mine Group (2709 ± 2 Ma, Nunes and Jensen 1980). These massive sulphide deposits have accessory economic quantities of silver, gold, tin, and cadmium.

The most favoured model for the formation of massive copper-zinc-lead sulphide deposits consists of hydrothermal solutions coming to surface and sub-aqueously forming syngenetic sedimentary and near-surface mineralization proximal to volcanic vents during periods of relative quiescence (Walker *et al.* 1975). Directly below the massive mineralization, the older volcanic rocks exhibit "pipes" of alteration and mineralization through which the hydrothermal solutions reached the surface. In the Noranda Mining Camp, several massive sulphide deposits occur at the same stratigraphic level, but others are situated at different stratigraphic levels in the volcanic pile (Spence 1975).

The hydrothermal solutions responsible for the mineralization are thought to be a result of seawater circulating through the volcanic pile and discharging near its core. Metals are leached from the surrounding volcanic rocks and precipitated in the zone of discharge. Widespread leaching of copper, zinc, and lead and associated alteration phenomena, however, has been difficult to detect in the volcanic rocks of the Noranda area.

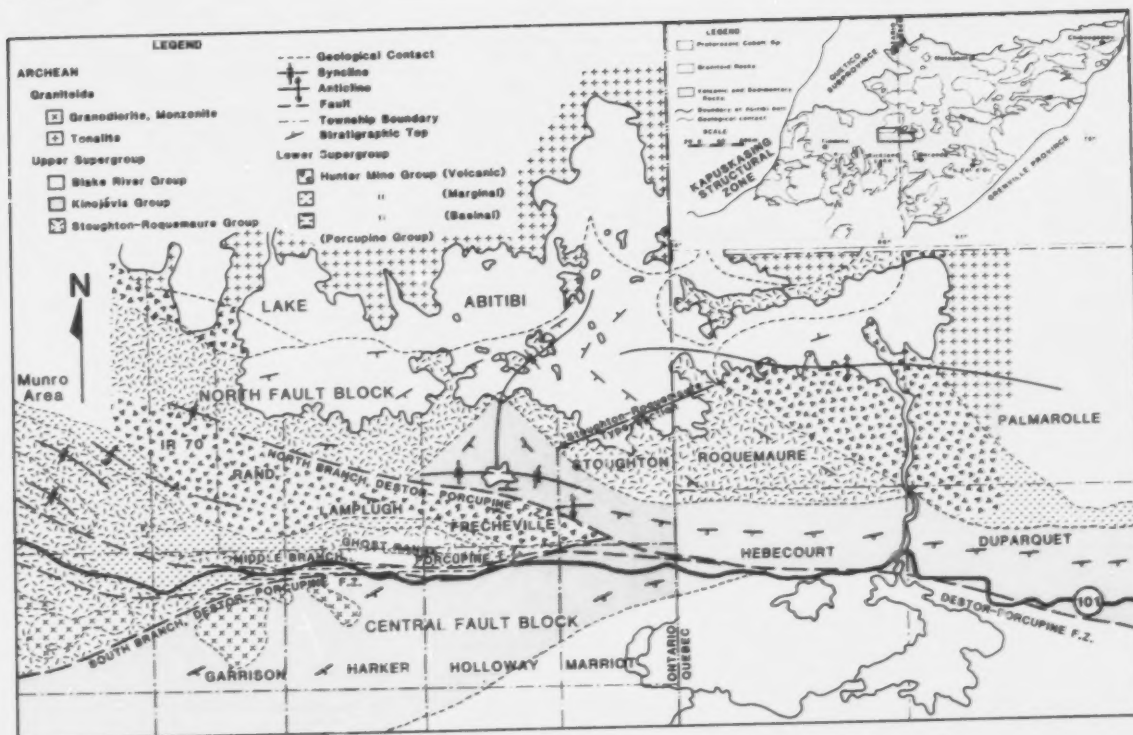


Figure 5.7. Geological map of the Lake Abitibi area.

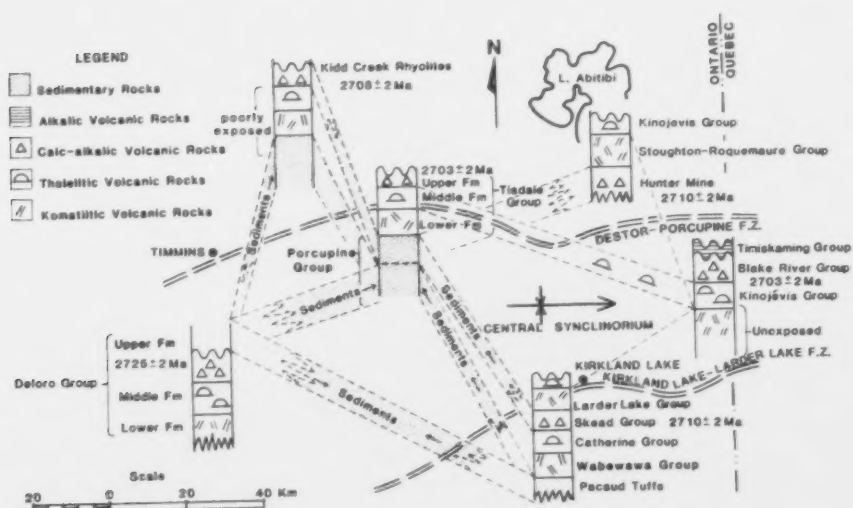


Figure 5.8. Regional stratigraphic correlation for the eastern part of the Abitibi Subprovince.

TABLE 5.2: STRATIGRAPHY OF THE VOLCANIC SEQUENCE IN THE WESTERN PART OF THE ABITIBI BELT.

	SOUTH OF TIMMINS	NORTH OF TIMMINS	LAKE ABITIBI	QUEBEC	KIRKLAND LAKE
UPPER SUPERGROUP					
	Upper Fm Tisdale Gr 2703±2		Blake River Gr 2703±2	Blake River Gr 2703±2	Blake River Gr
	Middle Fm Tisdale Gr		Kinojevis Gr	Kinojevis Gr	Kinojevis Gr
	Lower Fm Tisdale Gr	Lower Fm Tisdale Gr	Stoughton- Roquemaure Gr	Malartic Gr	Larder Lake Gr (Sedimentary and Volcanic Rocks)
LOWER SUPERGROUP II	?			Lois Fm	
	Porcupine Gr	Kidd Creek Rhyolite 2708±2	Hunter Mine Gr 2710±2		Skead Gr 2710±2
					Catherine Gr
					Wabewawa Gr
LOWER SUPERGROUP I					Pacaud Tuffs
	Upper Fm Deloro Gr 2725±2				
	Middle Fm Deloro Gr				
	Lower Fm Deloro Gr				
SOURCES OF INFORMATION	Pyke (1978a, 1978b, 1982) Nunes and Pyke (1980)	Pyke (1982) Nunes and Pyke (1980)	Jensen (1978b) Nunes and Jensen (1980)	Dimroth et al (1982, 1983a, 1983b) Nunes and Jensen (1980)	Jensen (1978c) Nunes, Pers. Comm. (1981)

An alternative model can be suggested if the premise that calc-alkalic volcanic rocks are the product of 10% partial melting of tholeiitic and komatiitic volcanic rocks of Jensen (1981a) is accepted. Low temperature melting components and most incompatible elements tend to be extracted during the early stage of partial melting and concentrated in the melt. For example, if the original partly melted mafic volcanic rocks averaged 50 ppm copper, the generated calc-alkalic volcanic rocks should contain >500 ppm copper rather than have an average of about 50 ppm copper. It is probable that much of the copper and other base metals are concentrated in the first 1% partial melt, which separates as a sulphide-rich hydrous solution from the silicate magma and is driven toward the surface by heat from the volcanism. Every 10 km³ of mafic volcanic rock that was partly melted would contain enough base metal to form a large sulphide deposit for each 1 km³ of calc-alkalic rocks formed.

In a vertically subsiding calc-alkalic volcanic pile such as the Blake River Group (Jensen 1981b), massive sulphide deposits could readily form in a "stacked" configuration at different stratigraphic levels, as well as occurring concentrated along specific stratigraphic levels as described by Spence (1975). In other megacauldrons where the calc-alkalic pile

has tilted sideways during its development (Figure 5.10), massive sulphide deposits would be more deeply buried and difficult to detect. Elsewhere, emplacement of large tonalitic batholiths in the calc-alkalic core of a megacauldron would cause massive sulphide deposits to be assimilated, and/or stopped away, or exposed and removed by erosion. This erosion would result in the dispersion of the base metals, iron, and sulphur into sedimentary rocks deposited on the margins of the calc-alkalic piles and in more distal basins.

Areas favourable for further base-metal exploration include the calc-alkalic volcanic rocks north of Timmins, the Shaw and Halliday Domes south of Timmins (Figure 5.4), the Hunter Mine Group south of Lake Abitibi (Figure 5.7), and the Blake River Group north of Kirkland Lake (Figure 5.6). Potential for base-metal sulphides also occurs in the eastern proximal facies of the Skead Group in Skead Township south of Kirkland Lake (Figure 5.5).

IRON ORE DEPOSITS

At present, the only banded iron formation being exploited for iron ore occurs at the Adams Mine in Boston Township south of Kirkland Lake (Figure 5.5). Here, iron formation is interbedded with cherty tuffs and carbonaceous pyritic cherts near the base of the

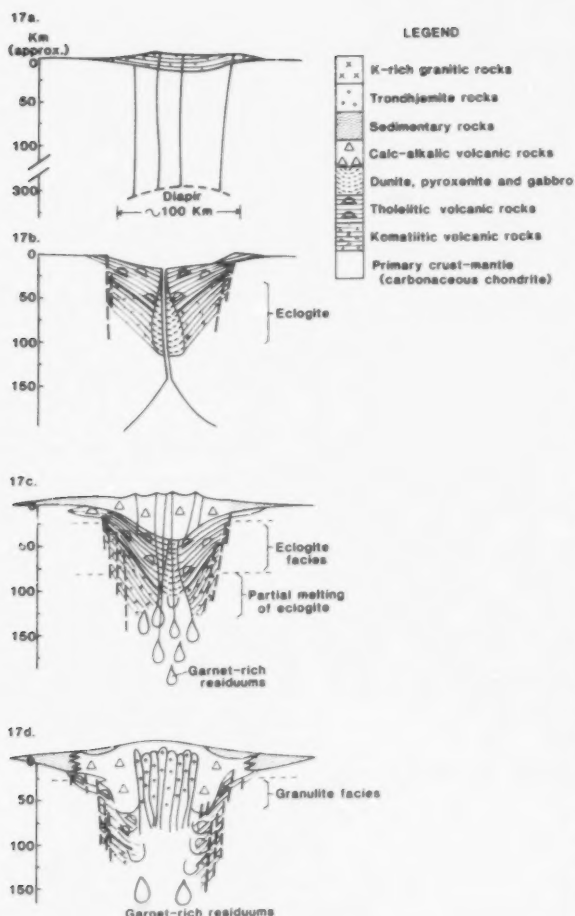


Figure 5.9. Development of a primary megacauldron above a mantle diapir: a) Diapir above which komatiitic flows accumulate; b) Subsidence of komatiitic flows and further accumulation of tholeiitic flows; c) Partial melting of komatiitic and tholeiitic rocks resulting in a calc-alkalic volcanic pile flanked by tuffs and sediments; d) Partial melting of calc-alkalic volcanic rocks resulting in tonalitic intrusions.

Larder Lake Group (Jensen 1978c). Komatiitic and tholeiitic lavas directly overlie and underlie the deposit, respectively. This iron formation was formed on the margins of the Skead volcanic pile shortly after komatiitic and tholeiitic lavas of the next volcanic cycle began to accumulate on its northern edge (Jensen and Langford 1985). Additional units of iron formation occur below the Larder Lake Group in the marginal depositional facies of the Skead Group (Jensen 1981a) and at the base of the volcanic succession in the Pacaud Tuffs (Figure 5.5).

In the Timmins area, iron formation occurs toward the top of the Upper Formation of the Deloro Group

around the Shaw Dome and farther south (Pyke 1978b, 1982) (Figure 5.4). Here, it is interlayered with calc-alkalic tuffs and grades into argillites and carbonaceous sedimentary rocks of the Porcupine Group. Iron formation is also intercalated with the distal tuffs and cherts of the calc-alkalic volcanic Hunter Mine Group (Dimroth *et al.* 1973; Jensen and Langford 1983) (Figure 5.7).

Thin beds rich in magnetite occur in the turbiditic sedimentary rocks of the Larder Lake, Pontiac, and Porcupine Groups. The deposition of banded iron formation and beds of magnetic clastic sediments appear to require shelf and basinal environments marginal to maturing calc-alkalic piles where periods of local volcanic quiescence commonly occurred.

Iron formation and clastic sediments rich in magnetite appear to be rare in volcanic successions where distal felsic tuffs and sedimentary rocks associated with calc-alkalic volcanism are lacking. Iron formation is limited to absent in the Stoughton-Roquemaure Group (Figure 5.7), Wabewawa Group, Catherine Group, the upper part of the Larder Lake Group (Figure 5.5), and the Kinojevis Group (Figure 5.6), which suggests that the development of iron formation is not favoured during komatiitic and tholeiitic volcanism. Banded iron formation is absent in the Blake River Group calc-alkalic volcanic rocks and in the proximal and central vent facies rocks of the Hunter Mine Group and Skead Group. Hence, the development of iron formation is largely limited to marginal and basinal depositional facies of calc-alkalic volcanic piles.

Exhalative and sedimentary models have been suggested to explain iron formation deposition. Alteration pipes which may be related to the development of overlying iron formation from exhalative fluids occur in the Wawa Greenstone Belt (Goodwin 1966). In the Timmins Kirkland Lake area, alteration pipes, however, have not been identified for any of the numerous units of iron formation. Unlike massive sulphide deposits which are lensoidal, banded iron formations tend to extend laterally for a km or more with constant thicknesses and are interbedded with relatively carbonaceous chert, cherty tuff, and argillites which may or may not contain disseminated sulphides. The absence of banded iron formation in the Blake River Group subaqueous proximal and near vent volcanic rocks suggests that iron formation tends to be developed in more distal parts of calc-alkalic piles as observed in the Skead and Hunter Mine Groups (Jensen and Langford 1983).

The strong association of iron formation with the felsic tuffs and turbiditic sedimentary rocks favours the model of Shegelski (1978) whereby iron formations are deposited in basins marginal to eroding volcanic piles. The silica and iron required for their formation were possibly derived from a distant volcanic exhalative source in the proximal or vent parts of calc-alkalic piles.

STRATIFORM GOLD MINERALIZATION

Stratiform gold deposits are those gold deposits and mines in which a significant part of their ore is hosted by carbonaceous mudstones, wackes, tuffs, cherts, iron formations and chemical carbonate-rich

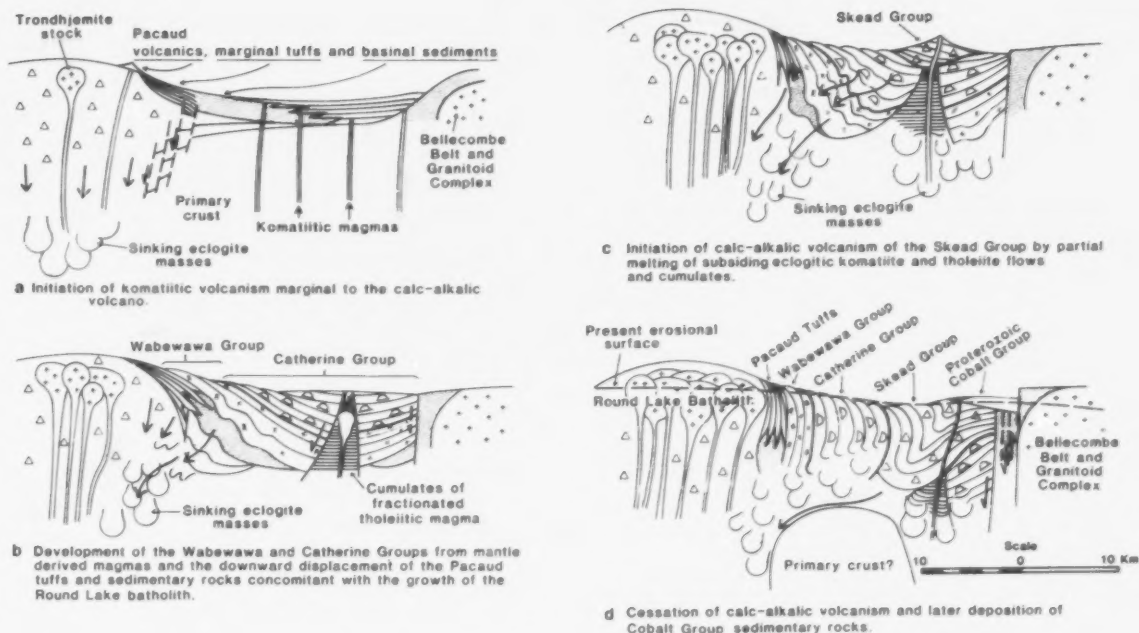


Figure 5.10. Development of a secondary megacauldron marginal to a primary megacauldron south of Kirkland Lake: a) Initiation of komatiitic volcanism marginal to the calc-alkalic Pacaud volcano; b) Development of the Wabewawa and Catherine Groups from mantle derived magmas and the downward displacement of the Pacaud Tuffs and sedimentary rocks concomitant with the growth of the Round Lake Batholith; c) Initiation of calc-alkalic volcanism of the Skead Group by partial melting of the subsiding eclogitic komatiitic and tholeiitic flows and cumulates; d) Cessation of calc-alkalic volcanism and later deposition of the Cobalt Group sedimentary rocks.

sedimentary rocks. These deposits include the Kerr Addison Mine and several smaller deposits in the vicinity of Larder Lake, and the Pamour, Hollinger, Owl Creek, and other major deposits in the Timmins area. Also there is the recently discovered gold mineralization east of Matheson in Holloway Township (see *The Northern Miner Press*, December 27, 1984 issue). All of these deposits are located near, but not directly on the Kirkland Lake-Larder Lake and Destor-Porcupine Fault Zones. The gold-bearing sedimentary rocks occur as interflow sediments to komatiitic and tholeiitic flows, or are interlayered with coarse mass flow turbiditic sedimentary rocks composed mainly of locally derived volcanic detritus.

The komatiitic and tholeiitic volcanic rocks of the Timmins and Larder Lake areas belong to the komatiitic successions at the base of the Upper Supergroup. In the Timmins camp, the flows form part of the Lower Formation of the Tisdale Group (Pyke 1982) (Figure 5.4), which correlates with the Larder Lake Group in the vicinity of Larder Lake (Figure 5.8).

In the Timmins and Larder Lake areas, the komatiitic and tholeiitic lavas and the interflow sedimentary rocks are part of volcanic sedimentary successions deposited on the margins of older calc-alkalic volcanic piles (Jensen and Langford 1985).

Detritus from those older calc-alkalic volcanic piles is also incorporated in the sedimentary rocks of the succession.

Several models have been proposed for the genesis of stratiform gold mineralization. These models can be group into three main types:

1. Gold was deposited with clastic and chemical sedimentary rocks (for example, Hinse 1984; Jensen 1981a).
2. Gold was precipitated at and near surface by hydrothermal solutions penetrating fractures along the major fault zones during the accumulation of volcanic and sedimentary rocks (for example, Fyon and Crockett 1983; Karvinen 1981).
3. Gold was concentrated epigenetically in the rocks along fault zones during late tectonism and felsic igneous activity (Hodgson 1983; Colvine *et al.* 1984).

In the first model, the source of gold is an older eroding calc-alkalic volcanic pile where volcanism and fumarolic activity had occurred or was still occurring and erosion of the pile was occurring. Gold was transported in solution, and in colloidal and detrital forms across the shelf of the volcanic pile and selectively concentrated in sedimentary traps along the tectonically unstable edges of the shelf at the

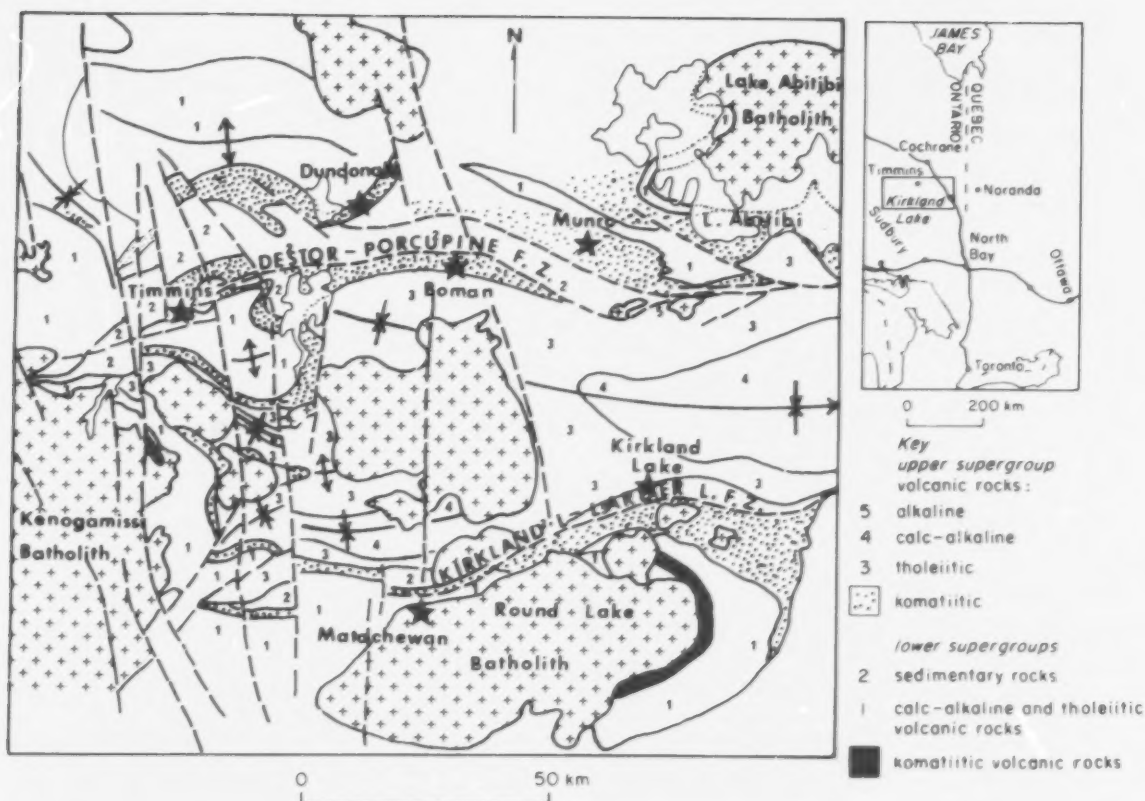


Figure 5.11. Distribution of komatiites and general stratigraphy in the Timmins-Kirkland Lake part of the Abitibi Subprovince (Jensen and Pyke 1982).

basin-shelf interface. The gold probably underwent several sedimentary reworkings prior to its final deposition with carbonaceous muds, carbonates, cherts, tuffites, and ferruginous sediments where sulphur-rich reducing environments prevailed (see Springer 1983). At the edge of the shelf, the gold-bearing sediments could be intercalated in a predominately sedimentary-tuffaceous succession as with other clastic sedimentary units as observed in the Hemlo deposits, or be interlayered with komatiitic and tholeiitic flows associated with a newly forming megacauldron as found in the Larder Lake and Timmins area.

In stratiform gold deposits, much of the gold occurs in quartz and quartz-carbonate veins and in shear zones which may have formed as a result of local komatiitic and tholeiitic volcanism and tectonic movements. Huppert *et al.* (1984) pointed out that sedimentary rocks overridden by komatiitic magmas at 1400° to 1700°C would be actively eroded and assimilated by the komatiitic lava, resulting in extensive contamination and alteration of the lavas and the overridden sedimentary rocks. Silica, carbon, carbonate, alkalis, and water within the sediments would be expected to strongly react with the magmas to

form magnesite, dolomite, talc, and fuschite. Gold and sulphides are concentrated along fractures and quartz veins.

The Kirkland Lake-Larder Lake and the Destor-Porcupine Fault Zones represent long-lived growth faults (Jensen and Langford 1985). After the development of a calc-alkalic volcanic pile with sedimentation along its margins, komatiitic and tholeiitic volcanism related to the next volcanic cycle began in the adjoining basins. As this occurred, the basin subsided with much of the displacement occurring along the basin-shelf interface where stratiform gold deposits had formed. This deformation and associated metamorphism caused some of the gold to migrate toward fractures (Jensen 1981b). This model explains why stratiform gold deposits and the major fault zones such as the Kirkland Lake-Larder Lake and Destor-Porcupine Fault Zones occupy the same geological environment. A basin was present between Timmins and Kirkland Lake with gold-bearing sedimentary rocks being deposited at approximately the same time on its northern and southern margins (Figure 5.8). Subsequent filling of the basin with rocks of the Upper Supergroup caused subsidence; much of the downward movement occurred along its

northern and southern margins forming the two major fault zones.

In the second model, Fyon and Crocket (1983) proposed that during the komatiitic volcanism and sedimentation, seafloor alteration occurred due to hydrothermal fluids consisting of modified seawater. These fluids penetrated upward via fractures associated with the Destor-Porcupine and Kirkland Lake-Larder Fault Zones and formed carbonate alteration zones in the volcanic rocks. During intervals of volcanic quiescence, exhalative action deposited auriferous cherty dolomite and pyritiferous graphite on the seafloor. Fyon and Crocket (1983) discounted the quartz-feldspar porphyries and the komatiitic lavas as being significant sources of the gold mineralization in the Timmins Mining Camp. More recently, Fyon *et al.* (1983) have suggested that gold was mainly introduced epigenetically by CO₂-rich fluids rather than during the deposition of the supracrustal rocks of the Timmins Mining Camp.

Support for the proposals of Fyon and Crocket (1983) and Fyon *et al.* (1983) comes from the abundance of carbonatized komatiitic flows and carbonate-rich sediments located near the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones. Although komatiitic and tholeiitic flows underlie large areas of the Abitibi Subprovince, the carbonatized komatiites and carbonate-rich sedimentary rocks are largely limited to the two major fault zones; they are not extensively developed elsewhere.

Zones of carbonatized komatiitic flows with extensive quartz veining are located in many places along the length of the two major fault zones and are not unique to the Timmins and Larder Lake Mining Camps. Many of these other zones of carbonatization have been subjected to intense exploration with little success, which suggests that factors other than just carbonatization and alteration must be critical to the development of auriferous rocks in the vicinity of the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones.

The epigenetic concentration of gold during late tectonism and felsic igneous activity forms the basis of the third group of models, and applies mainly to lode gold deposits discussed later in this paper. Hodgson (1983) and Colvine *et al.* (1984) have suggested that all the gold mineralization formed during a late stage cratonic stabilization of the Superior Province marked by felsic alkaline volcanism and intrusion and that gold was introduced by magmatic hydrothermal CO₂-dominated fluids. Support for this model comes from the close association between felsic intrusions and gold mineralization in lode deposits and the fact that gold in stratiform deposits is strongly associated with quartz veining, carbonate alteration, and tectonic deformation. Stable light isotope data suggest magmatic sources have influenced the mineralizing hydrothermal fluid in the deposits considered to be stratiform. Colvine *et al.* (1984) discounted sedimentary processes for concentrating gold and instead, suggested that chemical sediments such as carbonaceous rocks selectively collected gold during hydrothermal activity.

Several features of the epigenetic model conflict with field data. Much of the carbonatization found in

the komatiitic flows must have occurred syngenetically, definitely predating Timiskaming volcanism and sedimentation. Chemical and detrital carbonate units occur within the Larder Lake Group. Some are conglomeratic containing both carbonatized and noncarbonatized, spinifex-textured komatiitic clasts. Clasts of carbonatized komatiite commonly occur in carbonate-poor conglomerates. These sedimentary rocks are interlayered with carbonatized and noncarbonatized komatiitic lavas.

In the Timiskaming Group, extensive carbonatization is rare. However, carbonate detritus can be abundant in the basal conglomerates and in a few upper conglomeratic units higher in the Group, scattered carbonatized and noncarbonatized komatiitic pebbles can be easily recognized. Thus, this carbonate material appears to have been derived by erosion of the earlier formed Larder Lake Group (Jensen and Langford 1983). Along the Kirkland Lake-Larder Lake Fault, carbonatized komatiitic lavas and carbonate sedimentary rocks are juxtaposed against unaltered Timiskaming Group rocks.

Local carbonatization of komatiitic flows occurred during the emplacement of syenite, monzonite, and granodiorite bodies close to the Kirkland Lake-Larder Lake Fault Zone and the Destor-Porcupine Fault Zone. In these places, the intrusive rocks also have carbonate-rich phases, and it is probable that they assimilated carbonate during their emplacement. Away from the major fault zones felsic alkalic intrusive rocks and the associated carbonatization of the host komatiites sharply decreases; instead, talc and tremolite-rich rocks are formed where syenite, monzonite, and granodiorite cut the komatiitic flows.

The use of light stable isotopic evidence in support of the magmatic fluid model for gold deposits can be also questioned. Seawater during the Archean was buffered by mantle-derived volcanic rocks unlike present-day seawater which is buffered by continental rocks (Veizer *et al.* 1982, Veizer, 1984). Light stable isotope abundances in Archean seawater would be difficult to distinguish from those of magmatic origin derived from mantle and lower crustal sources. The mantle is poor in gold relative to other metallic elements, and, would probably have been depleted in gold by earlier melting episodes to form the host supracrustal rocks. Erosion of calc-alkalic volcanic piles would serve to further concentrate gold in restricted sedimentary environments of the crustal rocks.

NICKEL SULPHIDE DEPOSITS

In the western part of the Abitibi Subprovince, nickel sulphide mineralization occurs mainly near the base of the komatiitic Lower Formation of the Tisdale Group in the Timmins area (Pyke 1982) (Figure 5.4). The largest and best studied deposits include the Langmuir, Texmont, McWalters, Hart, Alexo, and Sothman Deposits (Coad 1979). Similar nickel mineralization occurs in Lamotte Township, Quebec (Marbidge Deposit) in the komatiitic flows of the Malartic Group, and in the komatiitic flows and intrusions south of Kirkland Lake and in the Munro Township area.

Disseminated low grade nickel mineralization is present in many of the large gabbroic sills north of

Timmins, particularly in the Kamiskotia Gabbroic Complex (Wolfe 1970). These sills, although tholeiitic in composition (Coad 1979), appear to be closely associated with the komatiitic and tholeiitic flows of the Lower Formation of the Tisdale Group (Pyke 1982).

The Lower Formation of the Tisdale Group and Malartic Group are correlated with the Stoughton-Roquemaure Group and Larder Lake Group (Figures 5.4, 5.5, 5.6, 5.7 and 5.8) (MEQ-OGS 1984). All four groups are considered to represent the komatiitic base of the Upper Supergroup formed during the development of the youngest megacauldron. These komatiitic lavas extended to overlap sedimentary and tuffaceous rocks deposited on the margins of calc-alkalic volcanic piles formed by earlier megacauldrons.

Sulphide mineralization consists of massive to disseminated pyrrhotite, pyrite, pentlandite, and minor chalcopyrite. Magnetite and chromite are common and millerite, violarite, heazlewoodite, and sphalerite can be present (Coad 1979). In the volcanogenic deposits, mineralization, particularly where massive, tends to be concentrated as nonconcordant lenses near the base of peridotitic komatiitic flows. In some deposits, mineralization extends upward into the middle and upper parts of the host komatiite unit; in others, mineralization locally crosscuts the base of the host komatiite and extends into the underlying rocks which are commonly calc-alkalic tuffs and tuff-breccias and carbonaceous mudstones with associated iron formation.

Four genetic models have been proposed to explain volcanogenic nickel sulphide mineralization (Coad 1979). Naldrett (1966) proposed a sulphurization model, whereby a reaction occurred between sulphur from an external source and nickel-bearing silicates. Sulphur could be introduced through melting of pyritiferous sedimentary and volcanic rocks by very hot (1400° to 1700°C) with much komatiitic lava (Huppert *et al.* 1984).

In a second model, Naldrett (1973) suggested that magmatic sulphides formed liquid droplets immiscible in the komatiitic magma brought up from depth. As the lava flowed out on surface, the droplets rapidly settled toward the base of the flow, concentrating close to the feeder.

To explain certain features of the Kambalda Deposits in Western Australia not adequately covered by Naldrett's second model, Ross and Hopkins (1975) proposed that a sulphide magma could separate ahead of the komatiitic flow, and later be overridden by the flow.

Lusk (1976) proposed a volcanic exhalative model to explain the abundance of pyrite and the presence of other base-metal sulphides in nickel sulphide deposits and in the underlying carbonaceous sedimentary rocks and iron formation which commonly form the footwall rocks. The exhalative model fails to explain the magmatic textures found in many of the deposits (Coad 1979).

Both the Abitibi and the Australian volcanogenic nickel sulphide deposits tend to occur in an environment where the host peridotitic komatiites have

flowed over calc-alkalic volcanic and sedimentary rocks (Coad 1979). In the Timmins area, the komatiitic flows overlie calc-alkalic volcanic rocks of different ages. South of Timmins, the calc-alkalic rocks are tuffs and tuff-breccias that grade into carbonaceous argillites and iron formation deposited at the edges of volcanic piles represented by the Upper Formation of the Deloro Group dated at 2725 ± 2 Ma (Jensen 1981b). During the calc-alkalic volcanism, tuffs and turbiditic sediments of the Porcupine Group (Figure 5.8) were being deposited in basins to the east of the Shaw Dome (Jensen and Langford 1983). Later, a second calc-alkalic volcanic pile developed north of Timmins (Kidd Creek Rhyolites, 2708 ± 2 Ma, Nunes and Pyke 1980), and more sediments were deposited in the areas to the southeast (Porcupine Group, Figure 5.4). A volcanic pile represented by the Halliday Dome also developed to the west of Matachewan. Following this calc-alkalic volcanism and sedimentation, widespread komatiitic volcanism was initiated in the basins between these calc-alkalic volcanoes. Komatiitic magmas cut through the calc-alkalic volcanic and sedimentary rocks forming stocks and sills and komatiitic flows (Pyke 1982). In places, nickel mineralization appears to have formed in the peridotitic komatiitic lavas as they came in contact with the various older rocks.

Sulphur-poor peridotitic lavas contain from 1500 to 2500 ppm nickel which is concentrated in the lattice of silicate minerals. Sulphurization of the basal peridotitic flows overriding pyrite-rich sedimentary and volcanic rocks appears to best explain the stratigraphic location of the nickel sulphide deposits. In many areas, particularly south of Kirkland Lake, peridotitic komatiites, however, can be observed directly overlying pyritiferous sediments and felsic tuffs without the development of nickel sulphides.

The immiscible liquid model does not easily account for the restriction of the largest sulphide deposits to the base of the komatiitic successions. This model requires that the initial magmas formed by partial melting of the mantle and incorporated most of the available sulphide liquid, leaving very little for subsequent magma batches.

The magmatic textures and the restriction of nickel sulphides to the base of the komatiitic succession poses problems for the exhalative model and for hydrothermal emplacement models that have been suggested. Even though some alteration is present near some nickel deposits, it is not as extensive as can be found elsewhere in the komatiitic succession, such as in zones around gold deposits and asbestos-magnesite deposits. The exhalative model would require nickel-bearing solutions reaching the surface to precipitate as nickel sulphides on the seafloor prior to the extrusion of komatiitic lavas. As the peridotitic komatiite lavas flowed over the sulphides, they would have to incorporate the sulphides to produce the flow to result in the observed magmatic textures.

Regardless of the model selected to explain sulphide mineralization, the most favourable environment, seems to be the lower contact of the komatiitic flows with iron formation, carbonaceous sediments, and/or calc-alkalic tuffs and flows. In the Timmins area, this environment is represented by the

komatiitic flows of the Tisdale Group where they are in contact with calc-alkalic volcanic rocks and associated sedimentary rocks of different ages.

Similar stratigraphic settings occur in the Kirkland Lake area (Figure 5.5) and the Lake Abitibi area (Figure 5.7). South of Kirkland Lake, peridotitic komatiitic flows of the Larder Lake Group and the Wabewawa Group are in contact with calc-alkalic tuffs, sedimentary rocks and tuffs of the Skead Group and Pacaud Tuffs, respectively. In the Lake Abitibi area, Stoughton-Roquemaure peridotitic komatiites overlie the calc-alkalic volcanic rocks, sedimentary rocks and iron formation contained in the Hunter Mine Group.

ASBESTOS, MAGNESITE, AND TALC DEPOSITS

In the western part of the Abitibi Subprovince, asbestos, magnesite, and talc deposits occur in ultramafic rocks associated with komatiitic volcanism at the base of the Upper Supergroup (Pyke 1982). The major asbestos deposits are in Munro and Garrison Townships south of Lake Abitibi, in Penhorwood Township west of Timmins, and in Midlothian Township near Matachewan (Figures 5.2, 5.4, and 5.7). Magnesite and talc deposits in Deloro Township south of Timmins (Pyke 1982) occur in large peridotitic sills which have extensive cumulates of olivine toward their base.

Many peridotitic-gabbro sills in the western part of the Abitibi Subprovince were explored in the 1950s and 1960s and were found to contain only minor amounts of asbestos. The main difference between economic and noneconomic sills appears to be the degree and type of alteration that took place during or subsequent to their emplacement. Pods and dikes of rodingite characterize the economic asbestos deposits. Zones of pervasive carbonatization can occur near and in contact with the asbestos mineralization (Satterly 1952).

Asbestos cross-fiber occurs in closely spaced, generally polygonal fractures associated with magnetite in massive serpentinitized dunites. The fractures may have been cooling fractures, along which hydrous fluids penetrated shortly after solidification, or later, during subsequent hydrothermal events. The asbestos deposits are located near, but not on the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones which may have been the foci of extensive fluid movement. The deposits contain footwall felsic tuffs and sedimentary rocks that may have once contained trapped pore fluids. These fluids percolated into the peridotitic sills because these footwall rocks underwent compaction and increased temperatures associated with the emplacement of the sills.

In talc and magnesite deposits, the dunites and peridotites, instead of being serpentinitized, have been transformed into talc and magnesite $\pm$ quartz by pervasive penetration of CO_2 -rich hydrous solutions (see Pyke 1982). The talc and magnesite deposits are hosted by strongly carbonatized mafic and ultramafic volcanic rocks.

Limited amounts of talc, magnesite, and serpentine slip-fiber are formed by the alteration and shear-

ing of peridotitic komatiite flows, both near alkali felsic intrusive bodies and along faults, particularly the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones. Chlorite, actinolite, quartz, and antigorite are associated with the mineralization. Along the fault zones, iron-dolomite, calcite, fuchsite, and in a few places, gold and sulphide mineralization can also be formed. However, gold and sulphide mineralization are notably absent in the major deposits of talc, magnesite, and asbestos, which again suggests that factors other than CO_2 -rich hydrothermal fluids were responsible for gold mineralization.

Peridotitic sills with olivine cumulates occur with numerous other small subcircular unfractionated peridotite plugs and stocks cutting the lower parts of the komatiitic succession of the Upper Supergroup and the underlying calc-alkalic rocks of the Lower Supergroups (Figures 5.4, 5.5, 5.6, and 5.7). They probably served as feeders to the komatiitic flows throughout the western part of the Abitibi Subprovince. From their distribution, they do not appear to have intruded along any particular fracture zone. There seems, however, to be greater potential for asbestos, talc, and magnesite in large layered sills with olivine cumulates in close proximity to major fault zones such as the Destor-Porcupine Fault Zone and the Kirkland Lake-Larder Lake Fault Zone.

LODE GOLD DEPOSITS

Several gold deposits in the western part of the Abitibi Subprovince appear to be epigenitically associated with the emplacement of late alkalic to subalkalic felsic porphyritic to granitic textured intrusions (Colvine *et al.* 1984). Gold mineralization is restricted to veins, fractures, alteration zones and metamorphic aureoles around these intrusions. In places, mineralization can be in the late granitic rocks themselves, either as disseminated gold, or gold concentrated in veins, fractures, and alteration zones. Included in this group of gold deposits are the gold mines located along the Kirkland Lake "Main Break" (Thomson 1950), the Ross Mine, Golden Arrow Mine, New Keloro Mine located near Matheson, the Young Davidson Mine at Matachewan, and the mineralization of the Garrison Stock in Garrison Township. The number of major economic gold discoveries directly associated with these late felsic intrusions; however, is small relative to the total number and volume of these intrusions, and most of the discoveries to date are limited to intrusions proximal the Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones.

The late alkalic to subalkalic felsic intrusions are part of a large suite of intrusive and extrusive rocks that is extremely variable in composition, texture, and distribution. The felsic end members consist of granodiorite, monzonite, quartz monzonite, syenite, and sodium-rich syenodiorite, but ultramafic, mafic, and intermediate phases including several varieties of lamprophyre are common. The extrusive equivalents show a similar range in composition.

The late felsic intrusive rocks differ substantially from rocks of the Round Lake and Lake Abitibi Batholiths. The late felsic intrusive rocks tend to be richer in alkalis, particularly potassium, and have more numerous inclusions of country rock than the

batholiths. Also the gneissic textures of the tonalitic-trondhjemitic batholiths is lacking in the late felsic intrusive rocks. The batholiths form domal structures at the base of the volcanic succession, whereas the late felsic intrusions tend to crosscut the rocks in all parts of the succession without appreciably doming the surrounding rocks.

The distribution pattern of the late alkalic intrusions does not suggest preferential intrusion along fault systems. The largest volume of these rocks occurs between the Destor-Porcupine Fault Zone and the Kirkland Lake-Larder Lake Fault Zone southeast of Timmins. The Watabeag Batholith composed of syenite and granodiorite, forms part of this group of intrusions. The second largest concentration is between the Round Lake Batholith and Kirkland Lake-Larder Lake Fault Zone, and another concentration occurs along the southern edge of the Destor-Porcupine Fault Zone from Timmins eastward to Harker Township (Figure 5.2). Alkalic intrusive rocks are rare, both north of the Destor-Porcupine Fault Zone and in the area underlain by the Blake River Group (Figures 5.6 and 5.7).

Alkalic volcanic rocks are abundant along the Kirkland Lake-Larder Fault Zone and along the Destor-Porcupine Fault Zone. They are interlayered with Timiskaming clastic sedimentary rocks, cut by the alkalic intrusive rocks. Porphyry clasts derived from the intrusions are found within the sedimentary rocks, further suggesting that the alkalic volcanic rocks and intrusive rocks are directly related.

Studies on the alkalic intrusive and extrusive rocks in the Kirkland Lake area (Watson and Kerrich 1983; Kerrich and Watson 1984) and in other Archean terrains (Arth and Hanson 1975), suggest that these rocks were derived from the partial melting of sediments at crustal depths. The distribution of the alkalic intrusive and extrusive rocks corresponds closely to the areas of deposition and deep burial of thick wedges of sedimentary rocks derived from the erosion of calc-alkalic volcanic piles (Jensen and Langford 1985) (see Figure 5.9). Before partial melting occurred, these rocks underwent deep burial caused by the younger accumulation of the 16 km thick Wabewawa-Catherine-Skead Supergroup and the 30 km thick Upper Supergroup (Jensen and Langford 1983).

With the exception of the Kirkland Lake "Main Break" zone and the Ross Mine, a very small proportion of the total number of alkalic intrusive bodies explored have yielded mineable tonnages of gold ore. Numerous small occurrences are present (Hodgson 1983) as would be expected if the alkalic intrusive and extrusive rocks were derived from the partial melting of sedimentary rocks with normal to slightly higher than normal background levels of gold and other elements Reimer (1984). The distribution of large mineable lode gold deposits associated with the alkalic magmatism suggests either that gold occurred in anomalous quantities in isolated parts of the precursory succession of sedimentary packages that were dehydrated and partly melted, or that gold was in anomalous concentrations in some of the rocks encountered by the alkalic magmas enroute to surface in the vicinity of the Destor-Porcupine and

Kirkland Lake-Larder Lake Fault Zones. The distribution of lode gold deposits closely coincides with areas favourable for stratiform gold mineralization in the vicinity of the major fault zones (see Stratiform Gold Mineralization). Lode gold deposits tend to occur on the downfaulted side of the major fault zones, and stratiform gold deposits tend to occur on the upsides, where the older rocks are still exposed. For example, along the southern side of the Kirkland Lake-Larder Lake Fault Zone are the stratiform Larder Lake Camp gold deposits; the Kirkland Lake Camp lode deposits occur on the northern downfaulted side (Jensen 1981a; Jensen and Langford 1985). Similarly, along the northern side of the Destor-Porcupine Fault there are the stratiform Timmins Camp deposits; the Golden Arrow, Ross, and Garrison lode deposits are found on the southern downfaulted side.

Careful study of the volcanic stratigraphy is required to predict the location of possible lode gold deposits. First, it is necessary to reconstruct the sedimentary facies relationship on the flanks of the older calc-alkalic volcanic piles, particularly where the more distal, gold-bearing shelf and basinal sedimentary rocks may have been deeply buried by younger ultramafic and mafic volcanic rocks. Second, it is necessary to look for structural discontinuities crosscutting the younger volcanic and sedimentary rocks and younger discordant intrusions which may have caused the remobilization of gold and allowed it to reach near surface along dilatant fracture zones. The Destor-Porcupine and Kirkland Lake-Larder Lake Fault Zones become broad dilatant zones near surface, and formed graben structures in which late Timiskaming sedimentary and volcanic rocks accumulated and were preserved (Jensen and Langford 1985).

SUMMARY

Mineralization in the western part of the Abitibi Subprovince is controlled, in large part, by volcanic and sedimentary stratigraphy. Specific suites of volcanic rock are favourable to certain types of mineralization. Massive copper-zinc-lead deposits, iron formations, and stratiform gold mineralization are associated with calc-alkalic volcanism; nickel deposits and asbestos, talc, and magnesite are associated with komatiitic volcanism; and lode gold deposits are associated with late alkalic to subalkalic felsic volcanism and intrusion. These suites of rocks occupy discrete positions in the stratigraphic column.

Mineralization is obviously not present everywhere within each of these favourable suites. Depositional environments conducive to the formation of a certain type of mineralization must be present while these rocks were being laid down, and these environments must since have been preserved close to the present bedrock surface for the mineralization to be of economic value.

To recognize environments favourable to mineralization, the explorationist must combine stratigraphic and structural data with a geological model concerning greenstone belt development. The megacauldron model of Jensen and Langford (1983) serves to show that base-metal, iron formation, and stratiform gold deposits occur, respectively, in the

depositional proximal, shelf, and basin edge environments of a maturing calc-alkalic pile, whereas, massive nickel deposits are formed where komatiitic flows lapped onto sedimentary and tuffaceous rocks associated with older calc-alkalic piles. Asbestos, talc, and magnesite deposits occur in olivine cumulates of sills near the base of the basal komatiitic successions where they could be penetrated by introduced CO_2 -rich and CO_2 -poor hydrous fluids. Lode gold deposits are preferentially located near major fault zones associated with late felsic intrusive and extrusive rocks. Their gold may be derived from deeply buried gold-bearing sedimentary and tuffaceous rock, originally deposited at the unstable shelf edge of a calc-alkalic pile.

Environments favourable for different types of mineralization commonly overlap, as observed in the Timmins area by Pyke (1982). Calc-alkalic piles were developed both north and southwest of Timmins, making the area favourable for base-metal, iron formation, and gold deposits. Komatiitic lavas and peridotitic intrusions lapped onto the edges of these calc-alkalic piles, and allowed massive nickel sulphide as well as talc and magnesite deposits to be formed.

In the Kirkland Lake-Larder Lake area, two calc-alkalic piles developed in succession south of Kirkland Lake. Iron formation and gold-bearing sediments were deposited on the northern shelves and basins followed by komatiitic volcanism and major faulting along the shelf edges of the volcanic piles. As a result, both stratiform and lode gold deposits are found in these areas along with iron ore deposits. Potential for base-metal deposits occurs in the near vent and proximal calc-alkalic volcanic rocks in the Blake River Group north of Kirkland Lake.

Environments favourable for the formation of base-metal, gold, nickel, and asbestos deposits similar to those of Timmins and Kirkland Lake are present along the Destor-Porcupine Fault Zone east of Matheson, south of Lake Abitibi, and along the Kirkland Lake-Larder Lake Fault Zone in the Matachewan area.

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Chapter 6

Developments in Stratigraphic Correlation: Western Uchi Subprovince

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ABSTRACT

The Red Lake and Uchi-Confederation Lakes Belts together form the western Uchi Subprovince, part of the Superior Province in Northwestern Ontario. In 1981, for the first time, geological mapping and radiometric dating permitted correlation of stratigraphy between these two Archean supracrustal belts. A three-fold stratigraphic subdivision of volcanic rocks (Cycles I, II, and III), previously established in the Uchi-Confederation Lakes area, was extended into the Red Lake Belt. Subsequent geological, geochemical, and geochronological tests of this correlation scheme, however, showed that some assumptions made in the first comparison of the two belts were invalid, and led to extensive revision of the regional stratigraphic interpretation.

Base-metal deposits in the Uchi-Confederation Lakes area, and gold deposits in both of these belts are believed to be, at least in part, stratigraphically controlled. The regional correlation presented allows the application of mineral exploration criteria developed in one belt, to the other, and calls attention to parts of the belts which have seen little prospecting activity in recent years.

Current mapping and research will determine whether the general stratigraphic scheme developed in this chapter can be applied to other supracrustal belts in the Uchi Subprovince, and to northern "greenstone" belts where mapping and preliminary geochronological data suggest comparable patterns of episodic volcanism.

INTRODUCTION

Several chapters in this Volume (Sage, Chapter 4; Jensen, Chapter 5; Trowell and Johns, Chapter 3) describe successful application of correlation techniques outlined by Trowell (Chapter 2) and Easton and Johns (Chapter 1). It is also useful, however, to

examine some of the problems inherent in attempting stratigraphic correlation and analysis in the Superior Province. This chapter represents a case study of attempts by the authors to correlate between the Red Lake and Uchi-Confederation Lakes greenstone belts (Figure 6.1), and to interpret relationships between stratigraphy and mineral deposits of the western Uchi Subprovince. The evolution of the stratigraphic scheme devised by the authors between 1981 and 1984 and the accumulation of new and more refined geological, geochronological, and geochemical data illustrate the need to carefully test fundamental assumptions upon which such interpretations are based. This history of incremental "improvement" in our understanding of the regional geology also suggests that the stratigraphic picture proposed later in this chapter should be viewed as only one more step in a long, intriguing process.

BACKGROUND: TWO SOLITUDES

Both the Red Lake and Uchi-Confederation Lakes Belts have long histories involving mineral exploration activity and government-sponsored geological surveys. The Red Lake Belt, the site of one of Canada's richest gold camps, has seen almost continuous Ontario Department of Mines-Ontario Geological Survey mapping since the 1950s, and has been explored for gold since the mid-1920s. However, the only comprehensive survey of the entire area was done by Horwood (1945). The many township-sized maps and reports published more recently are by several authors (Chisholm 1954; Ferguson 1965, 1966, 1968; Riley 1975, 1976, 1978a, 1978b; Pirie and Sawitzky 1977a, 1977b; Pirie and Grant 1978a, 1978b; Pirie and Kita 1979a, 1979b, 1979c), none of whom completed work on more than half of the 18 townships which make up the belt. This patchwork of geological information reflecting changes and refinements in geological mapping and interpretation over

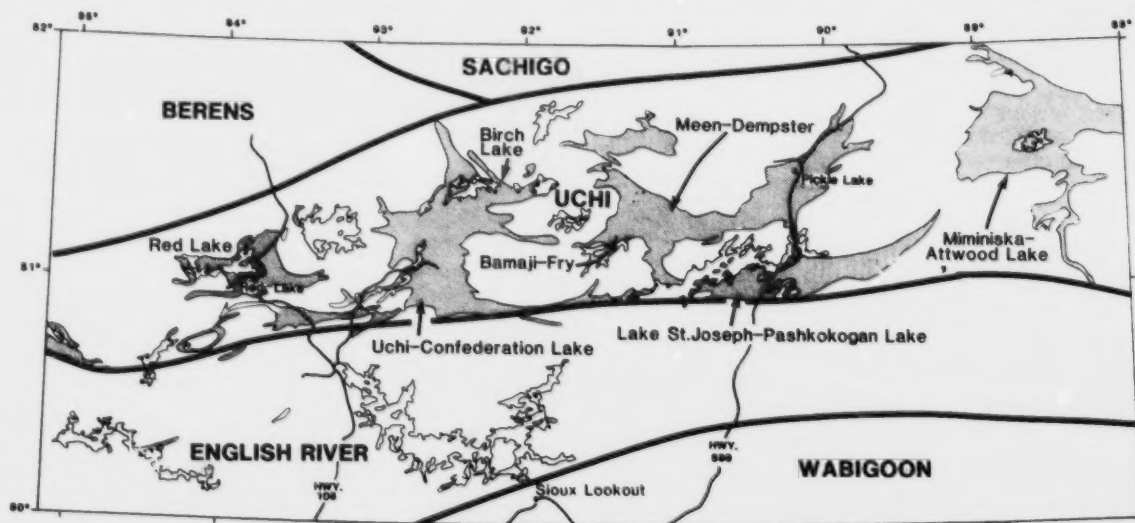


Figure 6.1. Location map showing the distribution of supracrustal belts (shaded areas) within the Uchi Subprovince of Northwestern Ontario.

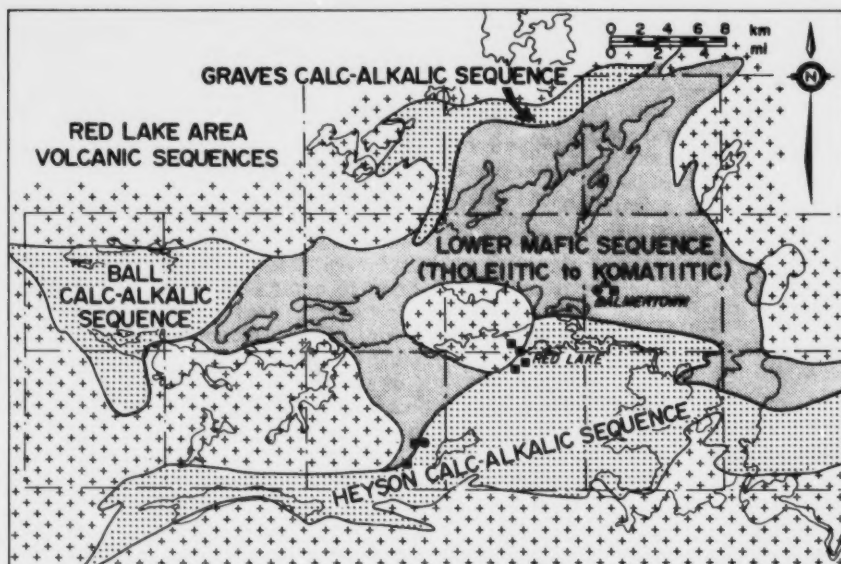


Figure 6.2. Stratigraphic interpretation of the Red Lake Belt (after Pirie 1981).

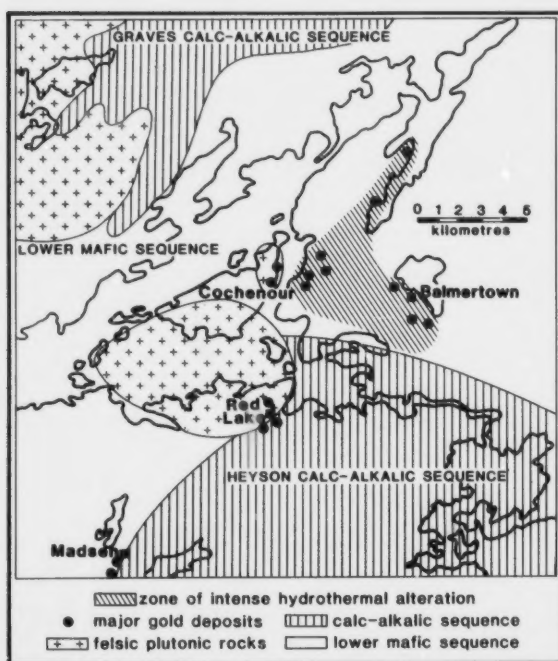


Figure 6.3. The first zone of pervasive hydrothermal alteration identified in the eastern part of the Red Lake Belt relative to major gold deposits and stratigraphic contacts (Pirie 1981).

the last 25 years, has made correlation within the belt difficult. Structural and stratigraphic patterns within the belt are still being unravelled.

Pirie (1981) made the first modern attempt to explain the gross tectonostratigraphic features of the Red Lake area based on his detailed mapping of the eastern part of the belt, reconnaissance mapping elsewhere, lithogeochemical data, and aeromagnetic patterns. According to Pirie (1981), the belt consists of two predominantly volcanic successions, a lower tholeiitic to komatiitic sequence underlying the axial portion flanked by calc-alkalic sequences occupying the northeastern, southeastern, and northwestern corners of the belt (Figure 6.2). These sequences were believed to form an anticlinorium, but in fact, few unequivocal facing directions and other structural data were available for most parts of the belt.

The other notable conclusion emphasized by Pirie (1981) was the spatial association between highly altered rocks in the lower tholeiitic to komatiitic sequence and most gold deposits in the eastern part of the Red Lake Belt (Figure 6.3).

By 1980, the southern part of the Uchi-Confederation Lakes area had been mapped in detail, thanks in large part to the discovery and development of the major copper-zinc deposits at South Bay on Confederation Lake in 1968. In the hope of finding more such deposits, the area was examined intensively by both government and exploration geologists between 1968 and 1980. Detailed published maps of the area include those by Pryslak (1970a, 1970b; 1971a, 1971b; 1972), Thurston *et al.* (1974; 1975a, 1975b, 1975c), Thurston and Jackson (1978), and Johns and Falls (1976a, 1976b). The results of these surveys allowed Thurston (1981a) to develop a comprehensive stratigraphic synthesis of this belt. Building on the work of Goodwin (1967) and Pryslak (1971a), Thurston recognized three volcanic cycles (Figure 6.4; Thurston 1981a). The overall structure of

the belt proved to be a simple synclinorium (Figure 6.5; Thurston and Jackson 1978). Base-metal deposits of the South Bay-type are restricted to the uppermost cycle, and are related to resurgent volcanism following the formation and subsequent collapse of a major caldera centred in that area (Thurston 1981a).

Detailed lithogeochemical studies in the Uchi-Confederation area showed that volcanic cycles are far from simple entities. The three cycles follow the classical mafic to intermediate to felsic trend described by Goodwin (1968). As in the Red Lake area, the overall trends are toward more fractionated volcanic products with time, however, both major and trace element patterns indicate the operation of a variety of complex magma-generating processes (Thurston and Fryer 1983).

At the top of the second cycle there is a distinctive chemical metasedimentary sequence including stromatolitic carbonate on Woman Lake (Thurston and Jackson 1978; Hofmann *et al.* 1985). Nunes and Thurston (1980) determined the ages of these cycles by applying the uranium-lead dating techniques of Krogh (1973, 1982a, 1982b) to zircons from the felsic rocks near the top of each cycle. The results (Figure 6.4), show that the difference in age between the youngest volcanic products in consecutive cycles is on the order of 100 to 130 Ma. The duration of individual cycles and the length of the hiatuses between cycles is unknown. This is a reflection of the paucity of dateable felsic volcanic material in the lower parts of individual cycles.

MISSING LINKS

On existing Ontario Geological Survey compilation maps of the western Uchi Subprovince, the area between Red Lake and Confederation Lake is largely uncoloured (Ferguson *et al.* 1970). Exposure is poor because of the thick glaciolacustrine silt-clay overburden, and most of the few known outcrops are of high metamorphic rank. These problems prevented effective stratigraphic correlation between the two belts until 1981.

During the 1981 field season, Thurston (1981b) succeeded in tracing volcanic units of Cycles II and III from Confederation Lake into the Gullrock Lake part of the Red Lake Belt (Figure 6.6), using detailed mapping, diamond-drill log data, and geophysical information made available by Selco Inc. In the same year, four uranium-lead ages on zircons from felsic volcanic rocks in the Red Lake Belt were determined (Thurston *et al.* 1981; Corfu and Wallace 1985). These four ages, 2982, 2830, 2739, and 2733 Ma, were originally obtained to test the tectonostratigraphic model that Pirie (1981) had proposed for the Red Lake Belt, and indeed they did corroborate the anticlinal nature of the belt (Figure 6.7). The very close agreement between these dates and those in the Uchi-Confederation Lakes belt, however, was quite unexpected, and suggested that a three-fold subdivision of volcanic stratigraphy might apply across the region.

In order to extend this temptingly simple correlation framework through the Red Lake Belt, a number of assumptions were made. The most convincing of these, at the time, pertained to carbonate units. A

stromatolitic marble unit overlying Cycle II volcanic rocks at Woman Lake in the Uchi-Confederation Lakes Belt; the felsic volcanic rocks below these carbonate beds have been dated at 2840 Ma (Corfu, unpublished data). At Red Lake, thick carbonate sequences occur in two places (Figure 6.6). In the central part of the belt, on northern McKenzie Island, a massive sequence of dolomitic marble at least 100 m thick occurs. This is immediately underlain by felsic to intermediate, heterolithic and monolithic pyroclastic beds, one of which was dated at 2830 Ma (Corfu and Wallace 1985). Hence, the McKenzie Island and Woman Lake carbonates appeared to occupy similar time-stratigraphic positions.

At the western end of Red Lake, another carbonate unit is exposed at and east of Pipestone Bay (Figure 6.6). North of the bay, these rocks have been metamorphosed to massive diopside-tremolite-grossularite-bearing skarns, but elsewhere the carbonate units commonly exhibit fine layering and other sedimentary structures, which in several places were positively identified as stromatolites (Riley 1972; Hofmann *et al.* 1985). Since stromatolite occurrences in the Archean rocks of the northern hemisphere are extremely rare, correlation between the Woman Lake, McKenzie Island, and Pipestone Bay carbonate sequences seemed a safe conclusion. Hence, the correlation of carbonate sequences formed the backbone in of the regional stratigraphic scheme outlined by Thurston *et al.* (1981) (Figure 6.8).

A second point used in the correlation was based on the assumption that the "mini cycles" defined by Thurston (1981a) in Cycle II at Confederation Lake as 60 to 120 m thick, mafic to felsic sequences each capped by chert and magnetitic iron formation, had stratigraphic equivalents in the Red Lake Belt. For example, on the southern side of Hoyle's Bay, mafic, intermediate, and felsic volcanic units are intercalated with chemical and clastic metasediments over comparable stratigraphic intervals. These sequences appear to be roughly on strike with the carbonates on McKenzie Island, assuming no major intervening structural dislocations. In the area west of Pipestone Bay, there is a similar rapidly alternating succession. Taken together the carbonate and mini cycle correlations led to the conclusion that much of the western and central parts of the Red Lake Belt were underlain by rocks equivalent in age, and possibly genetically related to Cycle II at Confederation Lake.

A SECOND LOOK

New Geochronology Data

In 1982, a second series of age determinations were made to test the proposed correlation pattern. The results of this series are summarized in Table 6.1 and Figure 6.9, and are obviously at odds with the authors' first stratigraphic interpretation of the Red Lake area. Although the new dates (column C, Table 6.1) fall roughly in the same age groups as the original Red Lake and Confederation Lake data (columns B and A, Table 6.1), the spatial distribution of the dated rocks clearly shows that the areas in the Red Lake Belt inferred to be of Cycle II age are much older, roughly equivalent in fact to the oldest cycle (2900 to 3000 Ma).

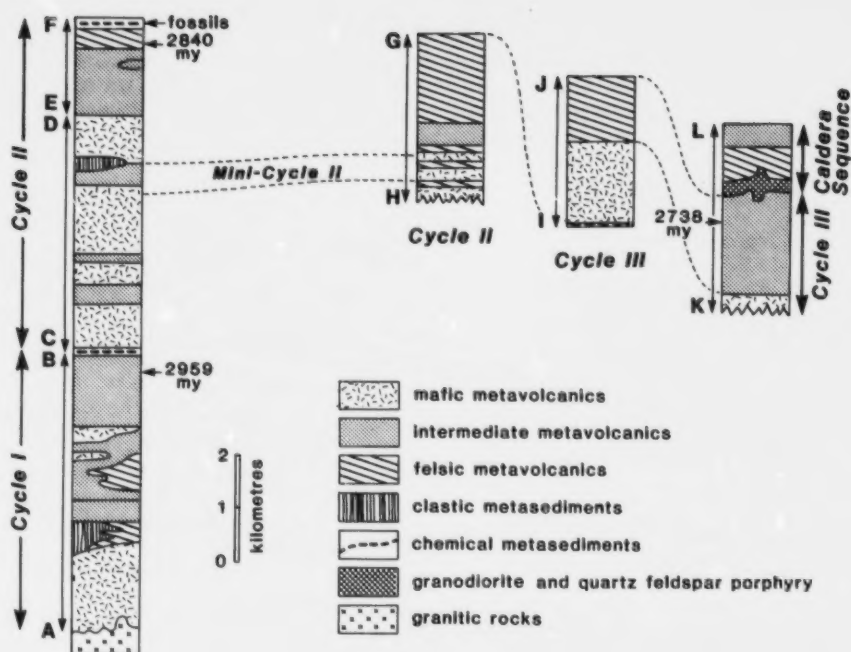


Figure 6.4. Stratigraphic sections in the Uchi-Confederation Lakes area (adapted from Thurston 1981a). Section lines are shown in Figure 6.5.

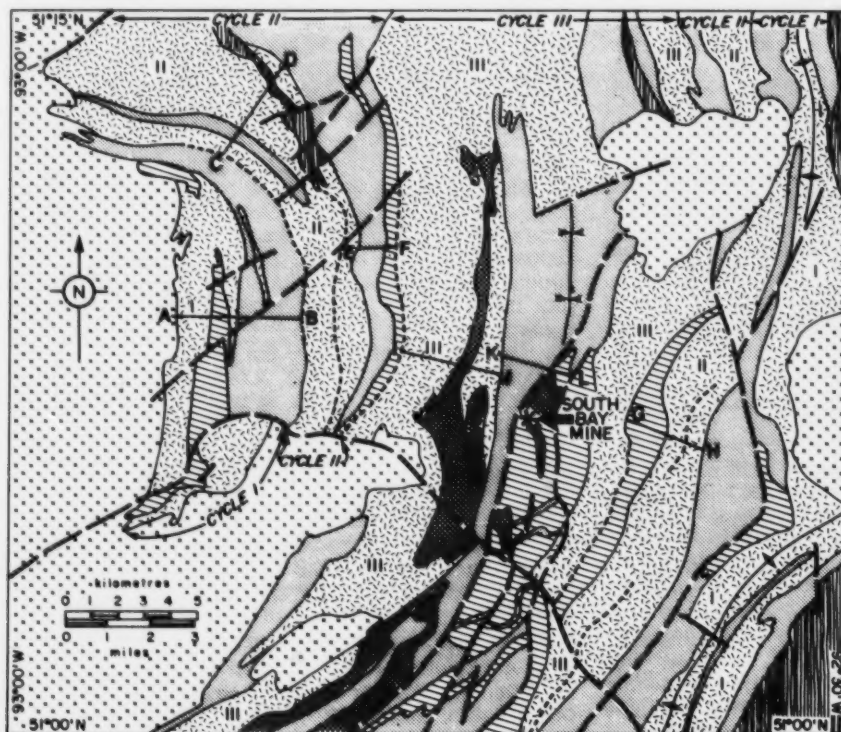


Figure 6.5. Geological map of the Uchi-Confederation Lakes area (after Thurston et al. 1978). Cross-sections are shown in Figure 6.4. Map legend identical to Figure 6.4.

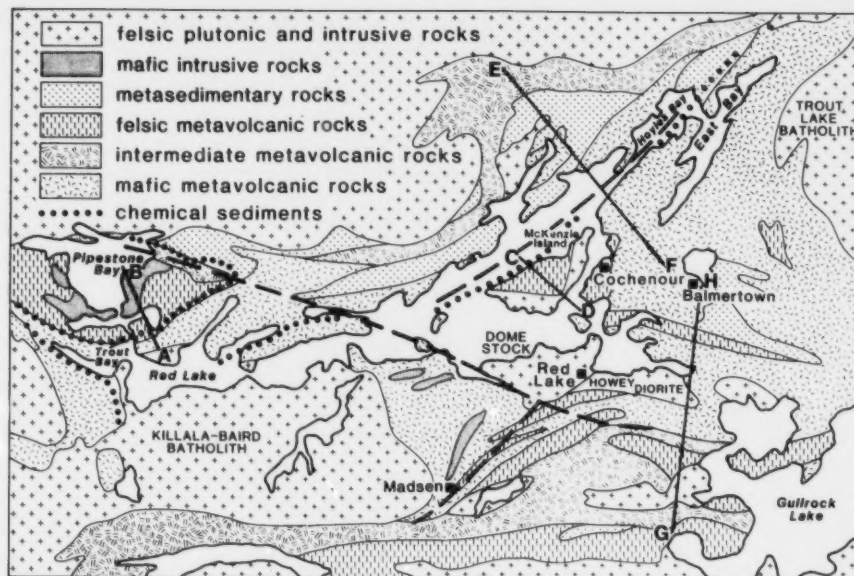


Figure 6.6. Geological map of the Red Lake Belt.

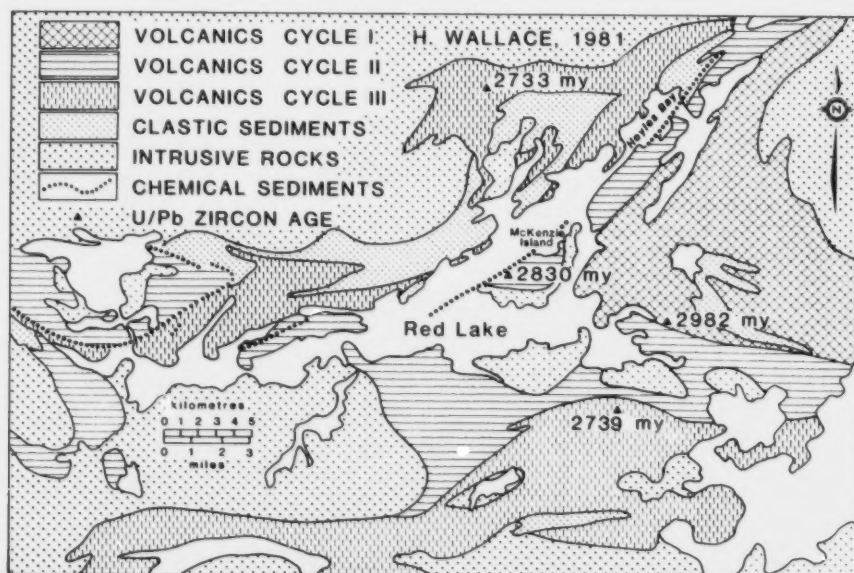


Figure 6.7. Stratigraphic map of the Red Lake Belt (Thurston et al. 1981). This interpretation was based in part on four uranium-lead zircon age determinations performed in 1981.

In the western part of the Red Lake Belt, felsic pyroclastic units just above and below the stromatolitic carbonate unit were dated at 2925 and 2940 Ma, respectively. These dates closely bracket the age of this marble, and discredited the assumption that it is time equivalent to the McKenzie Island and Woman Lake carbonates. Stromatolite-building organisms must have thrived in this region during two periods; between 2925 and 2940 Ma as around Pipestone Bay, and again after 2840 Ma at Woman Lake.

The date of 2992 Ma from felsic pyroclastic rocks on the southern side of Hoyles Bay prove that the mini cycles there cannot be of Cycle II age.

In fact, no additional ages comparable to Cycle II were obtained. The 2830 Ma date from northern McKenzie Island was then severely scrutinized to determine whether this unique age could be explained by the mixing of two generations of zircons, that is, from Cycle I (2900 to 3000 Ma) and Cycle III (2730 to 2750 Ma) rocks. Petrographic study confirmed that the dated rock is of heterolithic character; all of the fragments are of felsic to intermediate volcanic origin. Age determinations were then made on several carefully separated, morphologically discrete populations of zircons from that rock. In all, eight determinations were made, all of which indicated apparent ages between 2800 and 2835 Ma

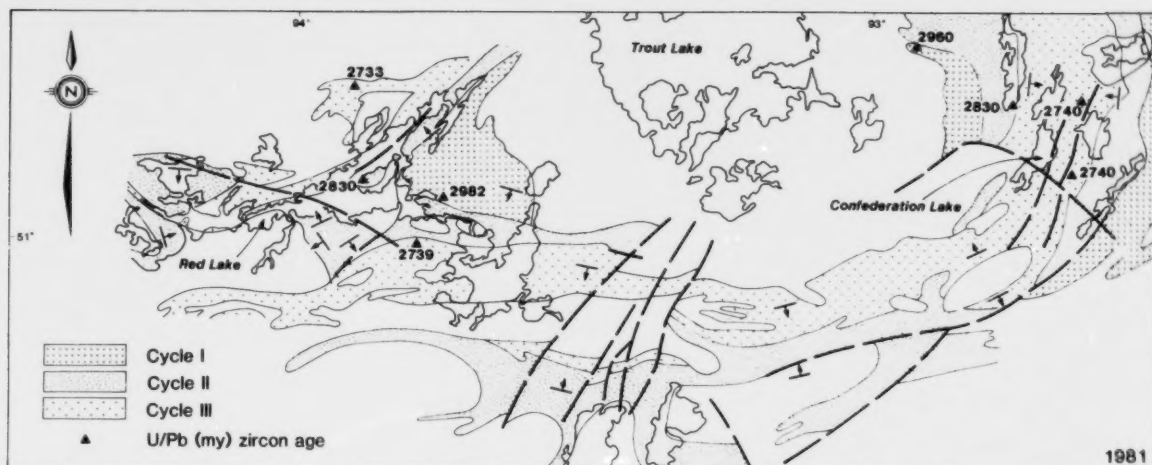


Figure 6.8. Original regional stratigraphic correlation map of the western Uchi Subprovince (Thurston *et al.* 1981), integrating local interpretations shown in Figures 6.5 and 6.7.

(Corfu and Wallace 1985). Clearly, the original volcanic rocks from which this heterolithic volcanoclastic unit was formed had crystallized at a time roughly equivalent to the Cycle II rocks at Confederation Lake. In fact, the spread of ages found may reflect the duration of Cycle II volcanism on a regional scale.

Another notable discrepancy between the authors original stratigraphic interpretation and the new geochronological data was evident south of Balmer-town. A sample from a sequence of felsic pyroclastic rocks, previously assumed to be of Cycle II age, was dated at 2748 Ma. That sample was collected <300 m from two sample sites to the north which gave an age of 2964 Ma. (The preliminary age of 2982 Ma reported by Thurston *et al.* (1981) was later shown to be too old due to the incorporation in the rock of inherited zircon; new determinations yield an age of 2964 Ma for the unit (Corfu and Wallace 1985)). A swamp between the two dated volcanic sequences precludes direct examination of the intervening stratigraphy; however, diamond-drill information suggests that they are separated by chemical and clastic metasediments. There is no evidence of Cycle II volcanic rocks in that area. An age of 2744 Ma was also obtained from a rhyolitic unit at or near the top of the tholeiitic to komatiitic sequence in Madsen (Corfu, unpublished data). The gap in time of at least 200 Ma over such a small stratigraphic interval can only be explained by the presence of a major break, either a fault or an unconformity, between the two volcanic sequences (that is, of Cycle I and Cycle III age).

New Geochemical Data

In 1982, chemical analyses from several areas of the Red Lake Belt became available, shedding new light on stratigraphic problems, and on the relationships between stratigraphy, alteration, and gold mineralization.

Of prime importance was the realization that the major and trace element compositions of volcanic rocks in the western part of Red Lake, in the north-central part of the belt, and in Baird Township, were quite similar to those documented in the Balmertown-Cochénour area (Pirie 1981). Komatiitic rocks and primitive tholeiitic basalts are the predominant lithologies in all of these areas. Rocks previously mapped as intermediate, calc-alkalic volcanic rocks in nearly all cases proved to be altered tholeiites. For example, in the western part of the belt, the Ball calc-alkalic sequence of Pirie (1981) in fact consists of a bimodal succession of tholeiitic basalts and calc-alkalic rhyolites, a fairly common Archean association (Thurston, Chapter 7, this volume).

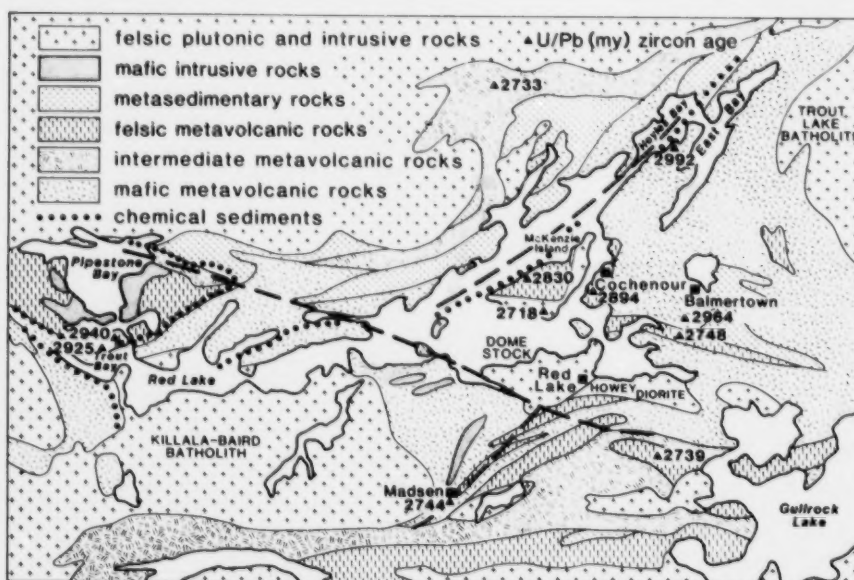
Basalts and rhyolites have been altered to varying degrees. In the case of the rhyolites, there is commonly little visible change with alteration, but chemically, sodium depletion, carbonatization, and both potassium depletion and addition are quite obvious. On the other hand, the mafic, and in some cases ultramafic volcanic rocks can be radically changed in appearance by pervasive alteration. On the basis of hand specimen examination alone, altered rocks are readily mistaken for andesites or dacites. In some cases, however, sodium depletion in such rocks gives rise to aluminous metamorphic assemblages commonly containing garnet and/or andalusite. In most such rocks, chemical criteria based on relatively immobile elements such as nickel and chromium clearly identify the mafic progenitors of these altered rocks. Their tholeiitic affinity can be assumed from their close spatial association with unaltered mafic volcanic rocks along strike and by their low yttrium and zirconium contents comparable to adjacent tholeiitic and komatiitic volcanic rocks.

Regional mapping suggests that the alteration zones are sub-conformable in the areas south and east of Pipestone Bay (Figures 6.6 and 6.10). These alteration zones include nearly all of the significant gold deposits and prospects found in this part of the belt so far. This spatial relationship and the general

TABLE 6.1: GEOCHRONOLOGY OF THE WESTERN UCHI SUBPROVINCE (U-Pb ZIRCON AGES IN MILLIONS OF YEARS).

CYCLE	UCHI- CONFEDERATION	RED LAKE	
		1981	1983
I	2959±2 ¹	(2982) ³⁻⁵	2992+20/-9 ⁴ 2964+5/-1 ⁴ 2940±2 ⁴ 2925±3 ⁴ 2894±1 ⁴
II	2840 ²	2830±15 ³	
III	2738+5/-2 ¹	2739±3 ³ 2733±1 ³	2748+10/-5 ⁴ 2744±1 ²

NOTES:

¹Nunes and Thurston 1980²Corfu unpublished data 1985³Thurston *et al.* 1981⁴Corfu and Wallace 1985⁵age too old due to incorporated inherited zircon; new determinations = 2964 Ma.**Figure 6.9. Geological map of the Red Lake Belt showing all geochronological data available in 1983.**

style of alteration are reminiscent of the situation described by Pirie (1981) within the "highly altered zone" around Cochenour-Balmertown (Figure 6.3).

In the Madsen area, detailed mapping and lithogeochemical studies by Durocher (1983) have shown that auriferous units, which were long assumed to be intermediate pyroclastic rocks, are in fact highly altered and deformed tholeiitic basalts. These rocks are similar, in terms of their trace element contents, to tholeiitic and komatiitic volcanic rocks elsewhere in Baird Township (Figure 6.11). Although differing in detail from the alteration in the Cochenour-Balmertown and Pipestone Bay areas, the general characteristics of all these zones are very similar. Again, the zones are crudely conformable

and occur near the top of the lower tholeiitic-komatiitic sequence. They do, however, appear to crosscut stratigraphy northeast of Madsen.

One interpretation of the distribution of alteration zones throughout the belt is that they are controlled by a conjugate set of large northeast- and west-northwest trending deformation zones (Figure 6.11; Andrews and Durocher 1983). These deformation zones appear restricted to the older (Cycle I) tholeiitic-komatiitic sequence; only the Pipestone Bay-St. Paul Bay Deformation Zone (Andrews and Durocher 1983) clearly transects stratigraphy.

On the southern limb of the Red Lake anticlinorium, that is, south of Madsen and Balmertown,

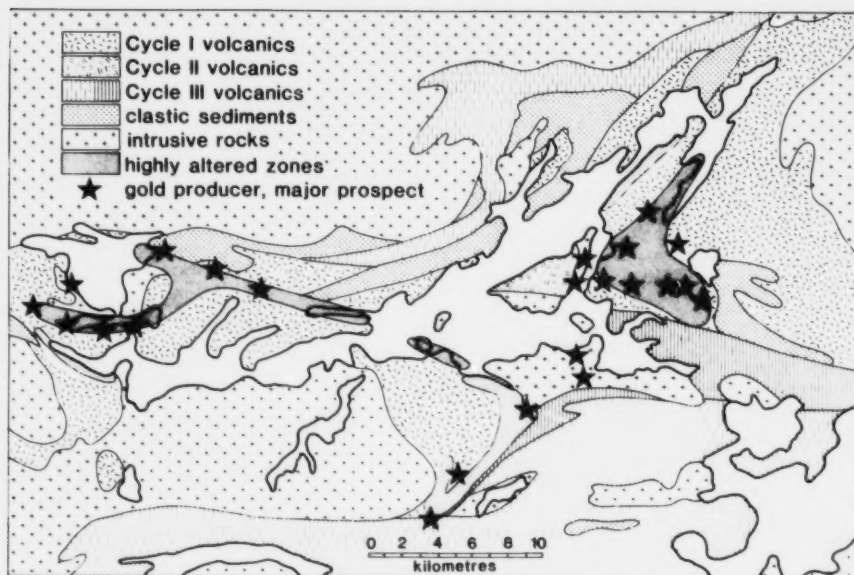


Figure 6.10. Distribution of zones of pervasive alteration in the Red Lake Belt relative to major gold deposits, based on data available in 1983.

two distinct tholeiitic sequences can be recognized. To the north, tholeiitic and komatiitic basalt flows of Cycle I age have primitive chemistry; the southern 2750 Ma old sequence includes variolitic basalts and andesites. On the basis of major element chemistry, this sequence is clearly tholeiitic, yet is highly evolved being characterized by zirconium and yttrium levels much higher than in the older tholeiites, and comparable to levels in the overlying calc-alkalic sequence. The younger tholeiitic sequence is similar, but measurably older than the predominantly calc-alkalic volcanic rocks which underlie most of Heyson Township. The younger tholeiites may represent a discrete stratigraphic package, or one gradational into the calc-alkalic rocks to the south.

On the northern limb of the Red Lake anticlinorium no sequence comparable to the younger tholeiites, described above, has been identified. The calc-alkalic volcanic rocks north of Red Lake are separated from the lower tholeiitic to komatiitic sequence by a thick unit of clastic metasediments. In general terms, these metasediments grade from wacke-mudstones, with intercalated polymictic conglomerate containing clasts of mixed volcanic origin, into a sequence of more mature arkosic sandstone and conglomerate beds with mostly clasts of felsic intrusive rocks. Although these rocks require much more careful study, the sequence appears to reflect a prolonged period of erosion of a complex volcanic terrain during which underlying batholiths were eventually exposed. This was presumably the result of a major tectonic event following the tholeiitic-komatiitic (Cycle I) volcanism and prior to calc-alkalic (Cycle III) volcanic activity.

The existence of this metasedimentary package suggests that the structural break inferred from geochronological and geochemical data south of Balmertown and Madsen is an unconformity. Because of its inherent weakness, this unconformity was a locus

for later tectonic movement which created the "deformation zone" evident in the Madsen area.

REVISED RED LAKE STRATIGRAPHY

On the basis of data collected in 1982 and 1983, the authors' stratigraphic interpretation of the Red Lake Belt was revised to that shown in Figures 6.12 and 6.13, and in the regional correlation map (Figure 6.14). The main change with respect to the 1981 versions (Figures 6.7 and 6.8) is the restriction of Cycle II to the area of McKenzie Island, and the expansion of Cycle I to occupy roughly 70% of the Red Lake Belt.

Cycle I, as shown in the new interpretation, includes rocks varying in age by almost 100 Ma (2992 to 2894 Ma). Clearly it constitutes a very complex stratigraphic sequence. It is doubtful that this package can be stratigraphically subdivided across the belt without much more geochronological work. The main reason for this is the strong probability that Cycle I and Cycle II rocks were subject to two major folding events. Cross folding is suggested in some areas by overturned minor folds, curving axial traces, aeromagnetic patterns, and, in a few cases, by the configuration of marker horizons. As previously discussed, a major folding event prior to Cycle III volcanism is required to explain formation of the thick sedimentary sequence between Cycles I and III north of Red Lake, and the apparent unconformity south of Balmertown.

The isolation of the small block of Cycle II pyroclastic and derived sedimentary rocks on McKenzie Island may be explained in a number of ways; original stratigraphic and/or structural boundaries of the block have been obscured by the Dome Stock and the waters of Red Lake, so it is difficult to evaluate these possibilities. The block may have been downfaulted or infolded into Cycle I, assuring

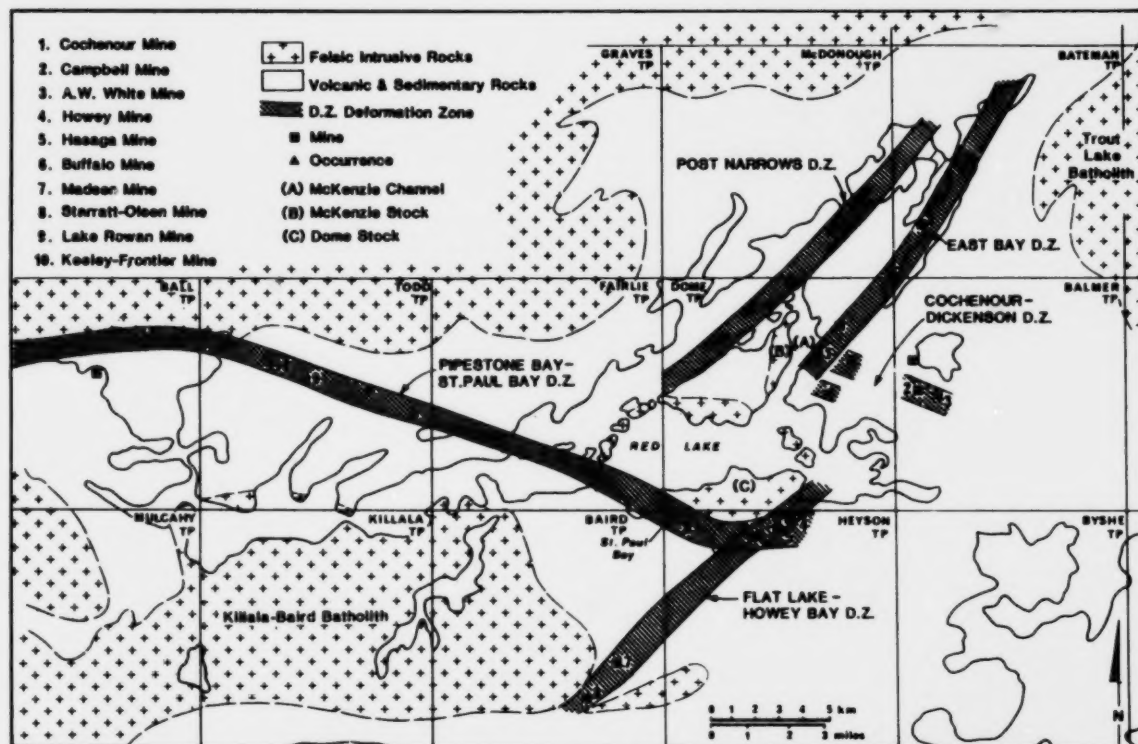


Figure 6.11. Location of deformation zones within the Red Lake Belt (after Andrews and Durocher 1983).

preservation while erosion removed all other traces of Cycle II rocks in the Red Lake area. Major strata-parallel faults, shown as the Post Narrows Deformation Zone on Figure 6.11, probably form the northern boundary of this block, and explain why older rocks on the northern side of Red Lake appear to overlie the Cycle II sequence.

A variety of felsic to intermediate lithic and pumiceous clasts and chert fragments are the main clast types in the volcanoclastic units on McKenzie Island. Similar rock-types form the subaerial and shallow water pyroclastic deposits (Thurston 1981a) on the western limb of the Uchi-Confederation Belt. Lithogeochemical evidence linking rocks from these two areas is as yet unavailable.

Although rocks of Cycle III age and character are traceable between belts, the continuity of individual units or formations is difficult to determine because of poor exposure and the high metamorphic grade of supracrustal sequences between the belts. The Cycle III volcanic rocks in the Red Lake area may, in fact, be products of a separate but similar eruptive centre.

ECONOMIC SIGNIFICANCE OF REGIONAL CORRELATIONS

Stratigraphy appears to be one controlling factor in the localization of base-metal deposits in the Uchi-Confederation Lakes Belt, and gold deposits in the Red Lake camp.

In the case of South Bay-type copper-zinc deposits in the Uchi-Confederation Lakes area, the relationship between mineralization and stratigraphy is easily documented and explainable on the basis of the Smith and Bailey (1968) caldera cycle. The deposits are believed to have formed syngenetically, at and near the rock-shallow water interface, during late stage hydrothermal activity within a collapsed caldera structure (Thurston 1981a). The mineralizing fluids were restricted to, and were concentrated in relatively small topographic features, the caldera itself, and adjacent grabens. Careful mapping, and facies analysis must be carried out to find these small, high potential, exploration targets in such complex volcanic environments.

Rocks comparable in age, stratigraphic position, and major element composition to the South Bay Mine sequence are now known to occur on both the northern and southern flanks of the Red Lake Belt. In light of this, these rocks should be evaluated geochemically to assess their genetic relationship with the South Bay Mine sequence. Comparison of trace element characteristics, combined with volcanic facies analysis between the two belts will perhaps determine whether similar mineralization can be expected around Red Lake. If the Red Lake rocks are distal, and were formed well outside the caldera environment, or if they prove to be products of an entirely different volcanic complex, then the chances of finding South Bay-type deposits are diminished.

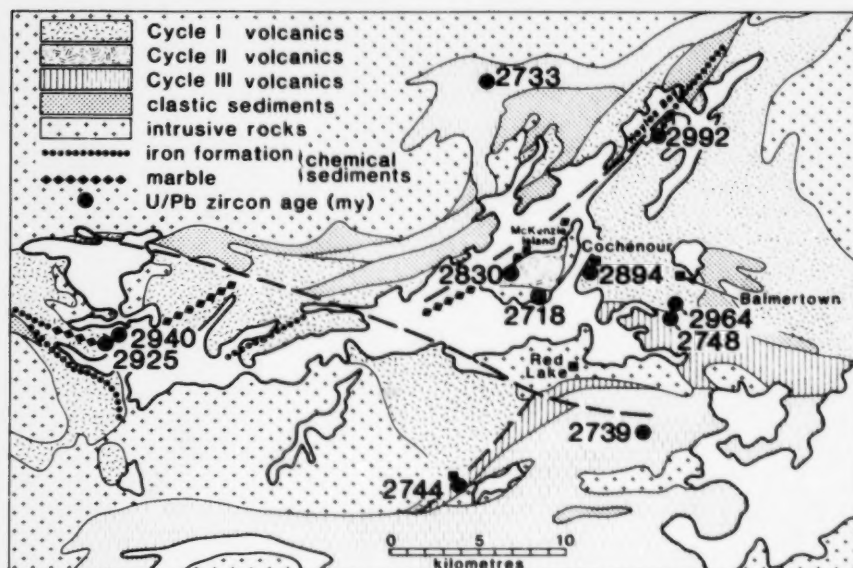


Figure 6.12.
Stratigraphic map of the
Red Lake Belt, 1983.
Interpretation based on
geochronological,
geochemical, and
geological data
accumulated between
1981 and 1983.

RED LAKE STRATIGRAPHY

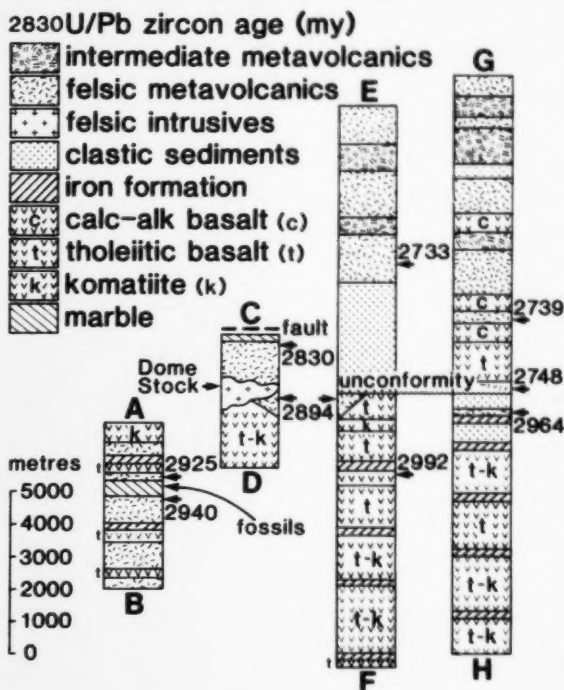


Figure 6.13. Schematic cross-sections through
parts of the Red Lake Belt. Lines of sections
are shown in Figure 6.6.

On the other hand, in more modern volcanic terrains, calderas tend to occur in "fields" in which several calderas follow similar patterns of evolution, and develop in close proximity at roughly the same time. Rocks of comparable age and chemistry throughout the region should be examined with this in mind.

The relationship between gold deposits and stratigraphy in the Red Lake Belt is less precise than for base-metal deposits in the Uchi-Confederation Lakes area. Empirically, a rather loose spatial correlation between Cycle I volcanic rocks, major zones of alteration, and gold deposits seems to apply in all parts of the Red Lake area. Conversely, very few deposits, and none of proven economic importance, have been found in areas underlain by Cycle II and III rocks, which constitute roughly 30% of the supracrustal belt.

At the detailed scale, the dominant factor controlling the location and character of ore zones in the area's past and presently producing mines is structure. The ore zones occur where deformation created volumes of rock in which low fluid pressures and high permeability permitted the easy movement of mineralizing solutions. Determination of the nature of these fluids, their source(s), the origin of the gold, and the reasons they preferentially affect rocks of Cycle I age are problems of considerable importance and controversy. They are not, however, easily resolved on either theoretical or empirical grounds, and will not be considered here. The authors, however, do suggest, based on the spatial association noted above, that some factor inherent in the stratigraphic make-up of Cycle I is particularly conducive to the formation of gold deposits. Hence, the identification of Cycle I rocks in other parts of the region is of economic significance.

Cycle I rocks in all parts of the Red Lake Belt continue to be prime targets for gold exploration. In the Uchi-Confederation Lakes area, these rocks are

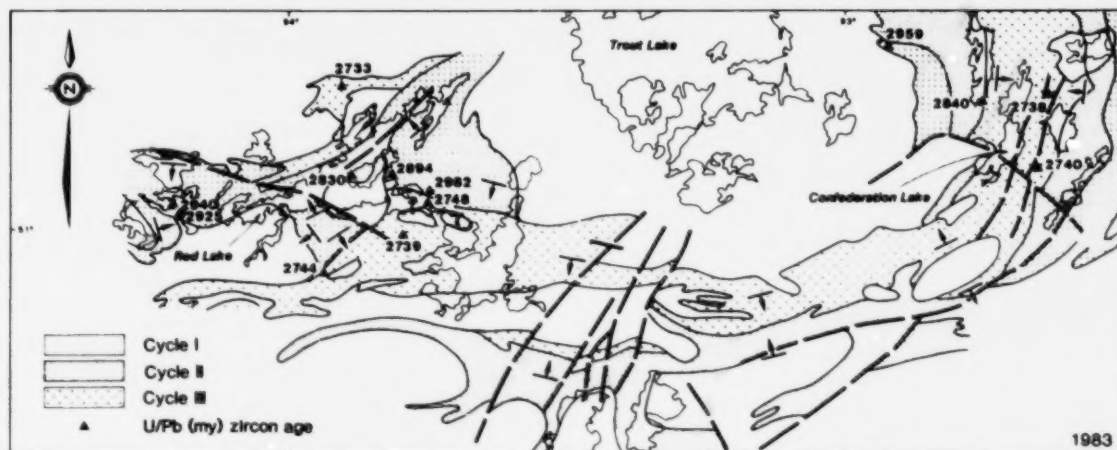


Figure 6.14. Stratigraphic map of the western Uchi Subprovince, 1983.

on the flanks of the belt. On the west, they occur north and south of Corless Lake, while on the eastern side of the belt they are found north and south of the Perrigo Lake Intrusion. In the Birch Lake area, Cycle I rocks have tentatively been identified around Seagrave Lake, and may occur elsewhere in the northern part of the belt. None of these areas has been intensively explored for gold in the past. Although gold has been mined in several parts of the Birch-Uchi-Confederation Lakes area, these previously known deposits are found in Cycle II and III rocks which occupy the core of the belt.

FURTHER REGIONAL COMPARISONS AND THEIR IMPLICATIONS

In parts of the central and eastern Uchi Subprovince (Figure 6.1) detailed geological mapping has also led to the recognition of polycyclic volcanism. In the Bamaji-Fry Lakes area, Wallace (1980) documented three lithologically and chemically distinct volcanic sequences. As in the Red Lake Belt, the youngest sequence appears to be separated from the older cycles by a marked unconformity. Geochemically, however, the patterns are quite different. Whereas chemical affinities in the Red Lake area change from dominantly tholeiitic-komatiitic to calc-alkalic with time, the sequence in the Bamaji-Fry Lake Belt is from calc-alkalic to tholeiitic, and finally to rocks of alkalic composition. In the Meen-Dempster Lakes Belt, Stott (1982; Stott and Wallace 1984) recognized at least two, and possibly three volcanic cycles on the basis of relative superposition. These sequences, not as yet geochemically characterized, may be traceable northeastward into the Pickle Lake area. In the southern part of the subprovince, Berger (1981) identified complex volcanic stratigraphy around the western end of Lake St. Joseph. Much farther to the east, Wallace (1981) reported at least three major volcanic sequences in the Miminiska Lake area. The second and third sequences are separated by an unconformity and a thick package of turbiditic metasediments.

It is unlikely that the stratigraphic patterns in these widely separated areas will ever be correlated directly. In many places once continuous supracrustal sequences have been completely dissected by plutons, and even where this has not occurred, the scarcity of outcrop makes it impossible to trace individual stratigraphic units. Hence, the only viable approach to long-range stratigraphic correlation is to compare these isolated, relatively well exposed and understood areas using geochronological data. Such dating programs are currently underway, but no results are yet available.

To the north, in the Sachigo Subprovince, geochronological studies have already been completed following detailed mapping in the North Spirit Lake (Nunes and Wood 1980) and Favourable Lake Belts (Corfu *et al.* 1981). Results of these studies are surprisingly similar to those from the western Uchi Subprovince. Major episodes of volcanic activity between 2910 and 3020 Ma and again between 2720 and 2740 Ma are common to these areas. The significance of these similarities is a matter of conjecture. It seems likely that a large part of the Superior Province was affected by a common sequence of magmatic events, the periodicity of which was governed by some first-order tectonic process. If such characteristics are common, exploration criteria developed in any one area on the basis of lithological, primary geochemical and stratigraphic factors may be much more widely applicable.

SUMMARY

The structural and stratigraphic complexity of Archean supracrustal terrain makes correlation between, and even within, individual greenstone belts difficult and uncertain. Tentative points of correlation based on lithological or chemical similarities must be tested carefully using independent criteria before marker horizons, such as rare carbonate units, can be relied upon.

On the basis of geochronological comparison, the authors have correlated major stratigraphic pack-

ages between the Red Lake and Uchi-Confederation Lakes Belts. Volcanic stratigraphy (Cycle III) can be traced between these areas; however, interbelt correlation of older units (Cycle I and Cycle II) remains tentative. Although volcanic sequences of broadly similar age occur within the two belts, much work must be done to determine how, or indeed whether these rocks are related genetically.

If the Red Lake and Uchi-Confederation Lakes areas share a common stratigraphic development, and if interbelt correlation can be refined, geologists can apply this concept as a powerful exploration tool. Exploration criteria developed here may also be applicable in other parts of the Uchi Subprovince to the east, and in supracrustal belts to the north where similar patterns of polycyclic volcanism are known or suspected.

The strong possibility that cyclic volcanism occurred in synchronous fashion over a wide area of the Superior Province is fundamentally significant when considering theories of Archean tectonics and crustal development.

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CHAPTER 6

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Part Three: Volcanic Lithogeochemistry and Mineral Exploration

Chapter 7

Volcanic Cyclicity in Mineral Exploration; the Caldera Cycle and Zoned Magma Chambers

P.C. Thurston

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ABSTRACT

Volcanic cyclicity pertains to the cyclic repetition of rock units. In the Archean, this has meant the repetition of mafic to felsic volcanism. Cyclicity occurs on several scales including 1) mini-cycles within single beds; 2) minor-cycles within 10s to 100s of m; 3) major-cycles within a few 100s to 1000s of m and, 4) super-cycles operative on the scale of 1000s of m.

The types of volcanic cycles commonly observed in the Archean are listed as follows: 1) Komatiite suite, peridotitic komatiite-peridotitic basalt komatiitic dacite; 2) Tholeiitic basalt-tholeiitic rhyolite; 3) Tholeiitic basalt-calc-alkalic felsic; 4) Tholeiitic basalt-calc-alkalic felsic tholeiitic basalt; 5) Komatiite suite peridotitic komatiite; 6) Tholeiitic basalt-calc-alkalic rhyolite-alkalic volcanic rocks; 7) Calc-alkalic basalt-calc-alkalic rhyolite.

Within these units are Fe and Mg enrichment and depletion cycles in komatiites and mafic rocks, and depositional and compositionally zoned cycles in felsic rocks. Geochemical data indicate the above cycles rarely represent continuous fractionation sequences. Therefore, hiatuses represented by clastic and chemical sediments occur frequently within them.

Volcanologically, gold can be related to iron enrichment cycles in basalts and associated hiatuses. In addition, gold can be related as well to volcanic-hydrothermal events involving hydro-fracturing of cherts and production of sedimentary barite units. Early epithermal veins directly relatable to volcanism are found in modern terrains, but not in the Archean. Most precious metal epithermal veins are related indirectly in terms of volcano collapse and so on, producing fracture sets or hiatuses in volcanism which allow the development of impermeable sedimentary caprocks.

Geochemical and volcanological observations allow ordering of many of the types of cycles and the chemically zoned magma chamber genetic hypotheses for volcanic sequences into the caldera cycle.

The caldera cycle was developed to explain the sequence of events in caldera development. The seven stages of the cycle are: 1) regional tumescence and generation of ring fractures; 2) caldera forming eruptions; 3) caldera collapse; 4) pre-resurgence volcanism and sedimentation; 5) resurgent doming; 6) major ring fracture volcanism; 7) terminal solfataric and hot-spring activity.

Volcanogenic massive sulphides are often associated with volcanic domes produced in stages 5 and 6 with some involvement of stage 7 fluids. This simplistic analysis does not explain the presence of basalts in mineralized felsic sequences or the unique heavy rare earth enriched character of copper-zinc mineralized rhyolites.

These features are explicable by invoking a chemically zoned magma chamber with a rhyolitic upper part in which large trace element gradients occur, and a basaltic lower part which is often erupted late in the eruptive sequence, yielding an association of high Fe tholeiites with copper-zinc mineralized rhyolites.

Field and chemical evidence for zoned magma chambers consist of: 1) mafic pumice toward the top of rhyolitic ignimbrites; 2) zonation in phenocryst type and abundance in felsic sequences; 3) the presence of minor cycles of basaltic andesite and rhyolite, with each rock type being of two distinct chemical types not inter-related by fractionation; 4) compositional zonation of stratigraphic sequences, for example at Confederation Lake Cycle III.

INTRODUCTION

This chapter treats the relationships between cyclicity in Archean volcanic stratigraphy, and the localization of mineral deposits by discussing:

1. *volcanic cyclicity*; the definition of the term, the various types of cyclicity found in "greenstone belts", the economic applications of various types of cyclicity, that is, location of mineral deposits in terms of volcanic cyclicity and a degree of stratigraphic control of some apparently epigenetic deposits.
2. *the caldera cycle*; how the complexities of stratigraphy can be analyzed in terms of the Smith and Bailey (1968) caldera cycle which involves large Plinian eruptions, collapse of an edifice forming a caldera, and renewed or resurgent volcanism. The caldera cycle and its reflection in regional stratigraphy permits the separation of felsic volcanic successions into those with high and low mineral potential with respect to volcanogenic copper-zinc massive sulphide mineralization.
3. *chemically zoned magma chambers*; their role in the genesis of massive sulphide mineralization and gold-silver deposits.

This chapter attempts to demonstrate that an appreciation of volcanic eruption processes and their products, the temporal succession of eruption types, and the character of the magma chamber from which the rocks are produced, can lead to a better understanding of mineralization in volcanic stratigraphy, and hence, and improved ability to evaluate mineral potential and locate mineral deposits.

DEFINITIONS

A cycle is defined as (AGI 1972): "A series of events or changes that are normally, but not inevitably, considered to be recurrent and to return to a starting point, that are repeated in the same order several or many times at more or less regular intervals and that operate under conditions which, at the end of the series, are the same as they were at the beginning." Cyclical volcanism pertains to the repetition of volcanic rocks. In the classical Archean context, this has generally referred to the repetition of sequences progressing from mafic to felsic (Goodwin 1967, 1968).

SCALE OF CYCLICITY

Anhaeusser (1971) examined cyclicity in Archean volcanic rocks and described its occurrence on four scales:

1. *mini-cycles*: measured in cm or parts thereof, for example, wacke-mudstone couplets or felsic tuff-chert couplets (Photo 7.1).
2. *minor cycles*: measured in m, 10s of m, 100s of m, for example, parts of Cycle II at Confederation Lake where basaltic andesite to rhyolite cycles take place over about 150 m intervals (Thurston 1981b) (Figure 7.1).
3. *major cycles*: "a few hundred to many thousands of metres" thick, for example, the cyclical volcanism of Ayres (1977) or Thurston (1981b) (Figure 7.2). Cyclicity on this scale occurs in the Norseman area of Western Australia (Doepel 1965; quoted by Glikson 1976) and in the Bulawayan Group of Zimbabwe (Bliss and Stidolph 1969).
4. *super cycles*: include the whole of a volcanic sedimentary to calc-alkalic to alkalic volcanic cycle and constitute 1000s of m of stratigraphy. In the Abitibi Subprovince, Pyke (1978) and Jensen (1978a) described the three-fold recurrence of a volcanic super cycle involving basaltic and peridotitic komatiite succeeded by high-Fe and high-Mg tholeiitic basalt through tholeiitic rhyolite to calc-alkalic basalt through rhyolite (Figure 7.3). Volcanic cycles of this magnitude appear to be unusual in their stratigraphic thickness and chemical variety. A further compilation of examples of the various scales of volcanic cyclicity is listed in Table 7.1.

TYPES OF CYCLICITY

Six major types of volcanic cyclicity recognized in the Ontario Archean based upon magma clan affinity are shown in Table 7.2. Three major magma clans are represented: komatiite, tholeiite, and calc-alkalic. Classification into these clans is, of necessity, a

somewhat arbitrary process. Glikson and Jahn (1984) have summarized investigations which have shown there is a compositional gap between komatiites (peridotitic, pyroxenitic, and basaltic) and the so-called high-Mg basalts. However, Johnson *et al.* (1978) have shown that a complete gradation exists between volcanic rocks of tholeiitic and calc-alkalic affinity. Therefore, in the following review of types of chemical cyclicity in Archean volcanism, the reader should realize that classification on the basis of an AFM or AFTM (Jensen 1976) diagram (that is, relative to a line separating rocks of two affinities) is not appropriate; rather, the presence or absence of the

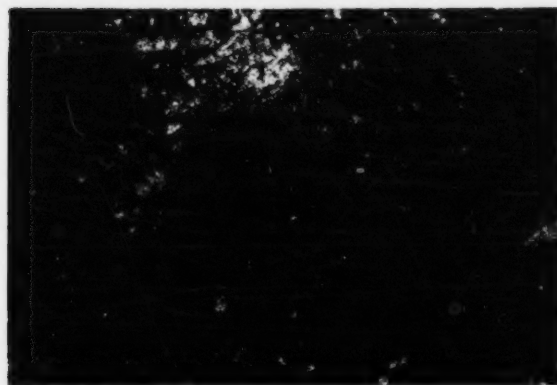


Photo 7.1. Compositionally zoned ash-flow from Cycle III Confederation Lake. Rhyolite fragments at base are shown by arrow. The unit grades upward to mostly andesitic pumice.

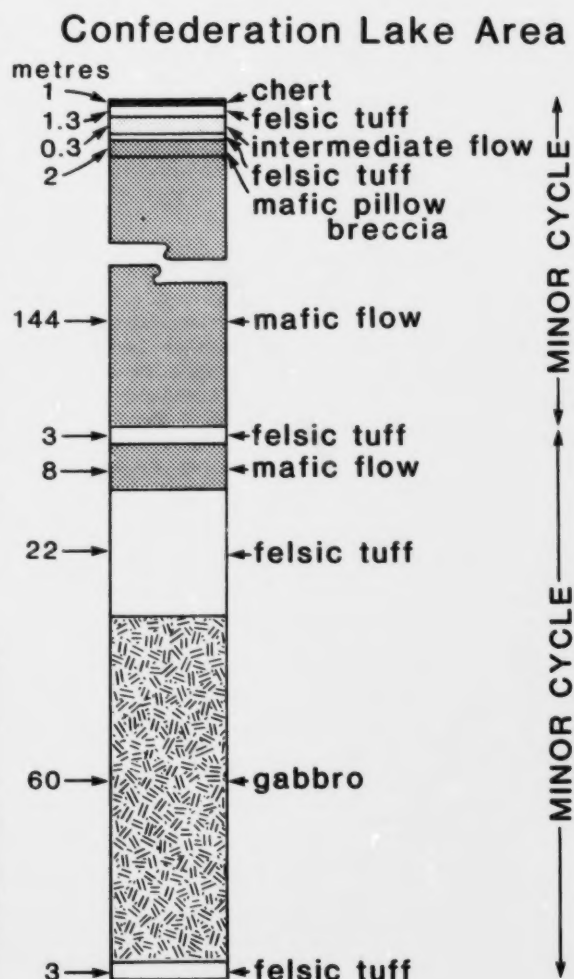


Figure 7.1. Minor cycle scale cyclical volcanism in Cycle II at Confederation Lake, stratigraphic section. The cycle progresses from mafic (basaltic andesite) flows to rhyolite tuffs and chemical sediments at the top.

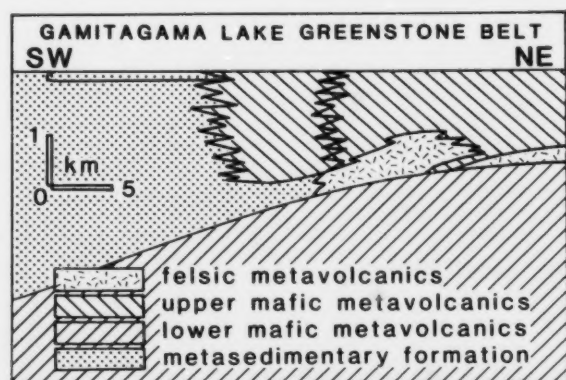


Figure 7.2. Major cycle scale cyclical volcanism in the Gamitagama Lake-Settling Net Lake area, Gods Lake Subprovince. Cyclicity is on the scale of 10^2 to 10^3 m (Ayles 1969).

hallmark of tholeiitic affinity, the iron enrichment trend must be tested for.

KOMATIITIC CYCLES

Within the komatiite class, Arndt (1975), Arndt *et al.* (1977), and subsequent workers (Nisbet 1982) have demonstrated that a fractionation (fractional crystallization) relationship exists between a parental magma of peridotitic komatiite through pyroxenitic komatiite, and that a hiatus in nickel, chromium, aluminium, and rare earth element data exists relative to high-Mg basalts of undoubted komatiitic affinity. The gap is explained by a model involving convection in a chemically zoned magma above primitive, freshly mantle-derived peridotitic komatiite (Nisbet 1982). The high-Mg basalts are the predominant units in these successions.

Field and chemical studies of cyclicity within these successions are important in that Arndt (1978) has observed that syngenetic nickel mineralization, exsolved immiscibly out of komatiitic liquids, is restricted to the Mg-rich part of the cycle as shown in Figure 7.4. Tholeiitic basalts and calc-alkalic pyroclastic rocks are intercalated within nominally komatiitic major stratigraphic units in the Abitibi Subprovince and at Red Lake. The origin of these units which mark the cessation of komatiitic volcanism is obscure; Glikson and Jahn (1984) suggested the units may have originated by partial melting of komatiites.

KOMATIITIC, THOLEIITIC, CALC-ALKALIC, ALKALIC CYCLES

Jensen (1978a) and Pyke (1978) have described cyclicity in the Abitibi Subprovince in which 2 super cycles have a komatiitic unit at the base surmounted by a tuff-chemical sediment unit together totalling 10 000 m in thickness, succeeded upward by a 6000 to 10 000 m thick tholeiitic unit, then a 7500 to 10 000 m thick calc-alkalic unit. The tholeiitic unit consists (Letros *et al.* 1983) of several minor-cycle-scale iron

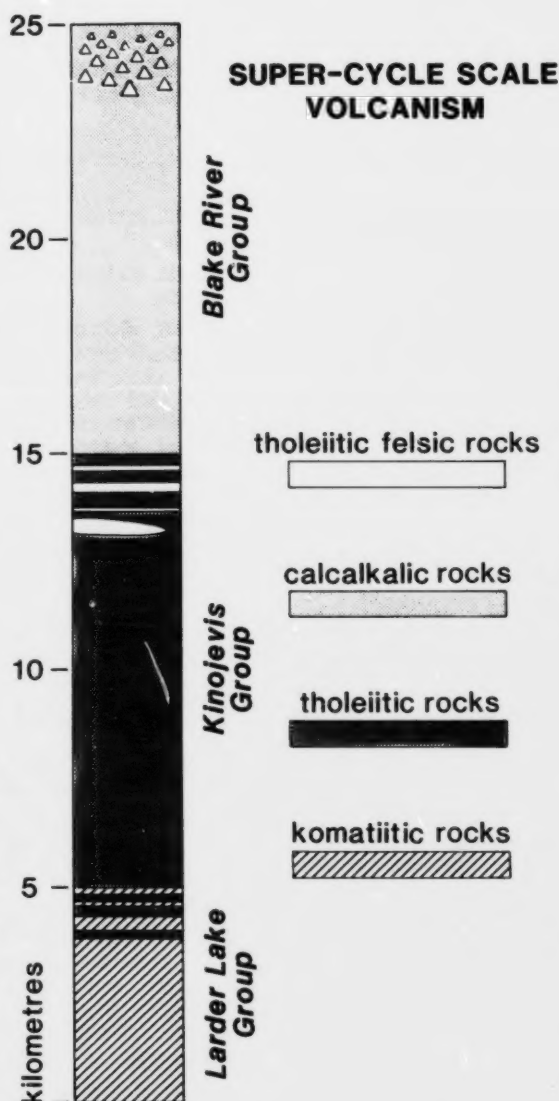


Figure 7.3. Super cycle scale cyclical volcanism in the Abitibi Subprovince. Jensen (1978a) postulated the existence of two super-cycles 10^4 m thick ranging from a komatiitic base through tholeiitic rocks, a calc-alkalic unit, to an alkalic volcanic top. This is a generalized cross section of Cycle II (after Jensen 1978b).

enrichment cycles, some of which evolve by fractional crystallization (Thurston 1981a) to rare tholeiitic rhyolite tuffs. The calc-alkalic unit consists of basalt through rhyolite characterized by lath-like plagioclase phenocrysts. Jensen (1984) suggested that rock types of this unit represent fractional crystallization from a calc-alkalic basalt parent magma.

These cycles are characterized by large scale cyclicity, that is, from komatiite through tholeiite to

TABLE 7.1: STYLES OF ARCHEAN CYCLICAL VOLCANISM.

AREA	UNITS REPRESENTED (AFTER WILSON <i>ET AL.</i> 1974)	SCALE OF CYCLICITY (AFTER ANHAEUSSER 1971)	REFERENCE
S. Africa (Onverwaacht Grp.)	Lower basic, middle basic	Super cycle, major cycle	Anhaeusser 1971
Rhodesia (Bulawayan)	Lower basic, middle basic, upper felsic	Super, major, minor, mini-cycles	Bliss and Stidolph 1969
W. Australia (Kalgoorlie)	Lower basic, middle basic, middle felsic	Super, major, minor, mini-cycles	
(Norseman)	Lower basic, middle basic, middle felsic	Major, mini, minor cycles	Doepel 1965
Canada Gods Lake Subprovince	Upper cyclic	Major, minor, mini-cycle	Hubregtse 1976; Ayres 1977
Wabigoon Subprovince	Lower basic, middle basic, middle felsic, upper cyclic, alkalic	Super cycle, minor, and mini-cycle	Blackburn, Trowell, and Edwards 1978
Abitibi Subprovince	Lower basic, middle basic, middle felsic, upper cyclic, alkalic	Super, minor, mini-cycle	Pye 1978; Jensen 1976, 1978a, 1978b,
Uchi Subprovince	Lower basic, middle basic, middle felsic	Super, major, minor, mini-cycles	This work; Wallace, personal communication, 1978

calc-alkalic volcanic rocks. Within each of these major magma clan units, there is minor scale cyclicity, particularly in the lower part of the super cycle. Within Quebec, in the upper part of Cycle III (MERQ/OGS 1984), G  linas *et al.* (1984) have observed minor scale cyclicity within the nominally calc-alkalic Blake River Group. This cyclicity consists of cycles, each 100s of m thick that have mafic bases of either tholeiitic or calc-alkalic affinity and progress upward to rhyolite. In fact, within the Duprat-Montbray Complex or cycle, four small scale basalt to rhyolite cycles exist (Thurston *et al.* 1984).

The minor scale cyclicity within the Blake River Group shows that small scale cyclicity exists within large scale cycles. The seemingly random alterations between tholeiitic and calc-alkalic affinity for the basaltic rocks of the Group (G  linas *et al.* 1984) suggest that the G  linas and Ludden (1984) hypothesis involving variable degrees of contamination as the explanation for the varying magma clan affinity of these units may be valid.

THOLEIITIC BASALT TO CALC-ALKALIC FELSIC VOLCANIC ROCKS

This type of cyclicity is probably the most common type in the Canadian Shield, according to surveys of Goodwin (1982) and Goodwin *et al.* (1982). This cyclicity consists of basal tholeiitic basalts and andesites succeeded upwards by calc-alkalic felsic volcanic rocks. Examples of such cyclicity include: Confederation Lake (Thurston 1981b; Thurston and Fryer 1983), Red Lake (Wallace *et al.* 1984; Pirie 1981), vast parts of the Wabigoon Subprovince (Trowell *et*

TABLE 7.2: TYPES OF ARCHEAN CYCLICAL VOLCANISM.

TYPES OF CYCLICITY
1) KOM perid kom — dacite
2) KOM perid kom — TH bas — rhy — CA bas — rhy — alk
3) TH bas — andes — TH andes — CA dac — rhy
4) TH bas — andes — CA bas — rhy — alk
5) CA bas — rhy
6) TH bas — CA dac — rhy — TH bas
KOM:komatiitic TH:tholeiitic — fractionation
CA:calc-alkalic alk:alkalic — no fractionation

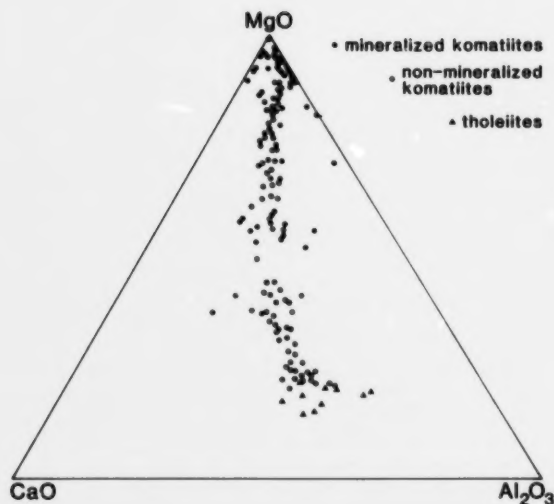


Figure 7.4. CaO-Al₂O₃-MgO (wt%) with komatiitic rocks of the Munro Township area (after Arndt 1978). The diagram illustrates the lack of major element discontinuities in this sample suite, the round filled symbols are komatiites with associated nickel deposits.

al. 1980), and the Favorable Lake area (Ayres 1977). This type of cyclicity may be subdivided into two such types: a) bi-modal basalt-rhyolite type, and b) a full fractionation type.

Bi-Modal Type

Thurston *et al.* (1985) showed that the Blake River Group in the upper part of Cycle III in the Abitibi Subprovince was clearly bi-modal, based upon 2300 analyses in the Quebec part of the unit. The two end members are andesite and rhyolite (Figure 7.5). Bi-modal volcanic cycles with basalt and rhyolite end members are more common, with numerous examples being cited by Thurston *et al.* (1985).

This type of bi-modal volcanism must be reconciled with the data (Figure 7.6) obtained in a survey by Goodwin (1977). This compilation shows a decreasing volume % from basalt to rhyolite for the Confederation area and part of the Wabigoon Subprovince. These data are consistent with an origin of the sequence by fractionation from a basaltic parent magma. Thurston and Fryer (1983) have shown that intermediate compositions in Cycle II at Confederation Lake are produced by magma mixing of tholeiitic basalt and trondhjemite, crystallization from primary andesite melts, and fractionation of basaltic liquids. The available evidence shows that while basaltic liquids fractionate to andesites, more felsic differentiates are not produced. The apparent greater abundance of andesites in Goodwin's (1977) compilation may have been produced by sampling of heterolithic pyroclastic rocks, or by the practice of chip sampling which can incorporate altered pillow

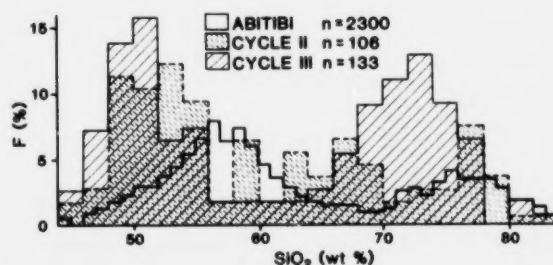


Figure 7.5. Histogram of about 2300 analyses of Blake River Group volcanic rocks (after Thurston *et al.* 1985). Vertical axis number of samples; horizontal axis-volatile-free wt% SiO₂. The bimodal distribution of SiO₂ values is quite evident, clustered at andesite and rhyolite.

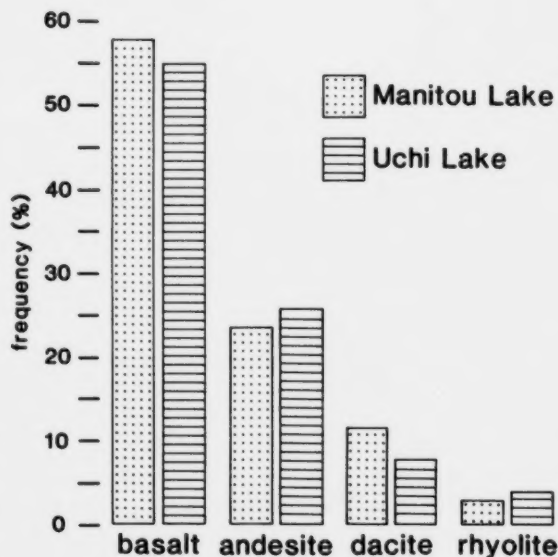


Figure 7.6. Histogram of volcanic classes Lake of the Woods-Wabigoon Subprovince (after Goodwin 1977). Vertical axis-weighted mean abundance based upon stratigraphic thickness; horizontal axis-generalized rocks types.

selvages, or the inclusion of several fragment types in the sample.

Thurston *et al.* (1985) have shown that bi-modal basalt rhyolite volcanism is the most frequently described type of volcanism in the Superior Province, based upon sedimentologic, volcanologic, and geochemical evidence.

Full-Fractionation Type

This type of cycle is represented by calc-alkalic volcanic rocks ranging in composition from basalt to

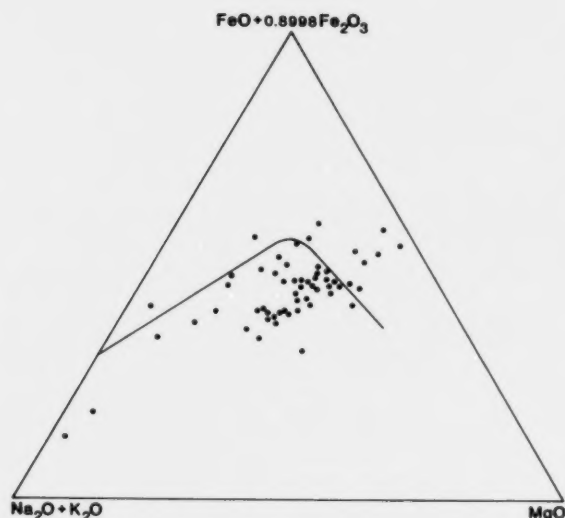


Figure 7.7. $\text{Na}_2\text{O} + \text{K}_2\text{O}-\text{FeO} + \text{Fe}_2\text{O}_3-\text{MgO}$ (AFM) diagram in wt% of the Yoke Lake volcanic rocks (after Thurston *et al.* 1984). The Yoke Lake sequence is of calc-alkalic affinity and is the youngest sequence in the Straw Lake area of the Wabigoon Subprovince. A complete data set would show a lack of compositional gaps in the suites.

rhyolite with no gaps in major element compositions. Trace element data exist for only a few suites, making petrogenetic conclusions tentative. Giles (1982), Giles and Hallberg (1982) and Hallberg *et al.* (1976) have shown that some of these complexes are produced by the melting of a mafic source in the lower crust, followed by fractionation in a high level magma chamber. Sparse data on Canadian examples suggest that the sequence at Yoke Lake in the Wabigoon Subprovince may be similar (G.R. Edwards, Professor, York University, personal communication, 1983).

THOLEIITIC BASALT-CALC-ALKALIC BASALT-RHYOLITE-ALKALIC VOLCANIC ROCK

This type of volcanic cycle, with an uppermost unit of alkalic volcanic rocks has been viewed as being relatively uncommon with the major example cited being Cycle III in the Abitibi Subprovince capped by the Timiskaming Group alkalic volcanic rocks (MERQ/OGS 1984). Jensen (1984) has noted, however, that the top of Cycle II in the Abitibi includes conglomerate with trachytic clasts. Other examples of this type of cyclicity include: the Wawa Subprovince west of Thunder Bay (Shegelski 1980); the Wabigoon Subprovince south of Dryden (Blackburn *et al.* 1984); the Birch Lake area of the Uchi Subprovince; and Oxford Lake Manitoba (Brooks *et al.* 1982). A number of gold deposits occur in the Kirkland Lake area that are spatially associated with plutonic equivalents to these volcanic rocks (Ploeger 1980); a spatial association of late volcanic rocks and gold also occurs at Shebandowan (Stott and Schnieders 1983).

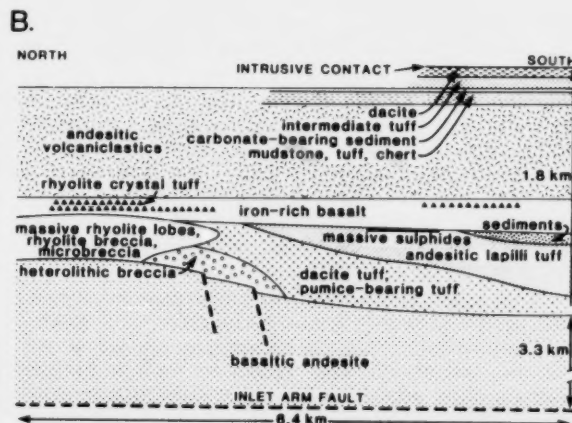
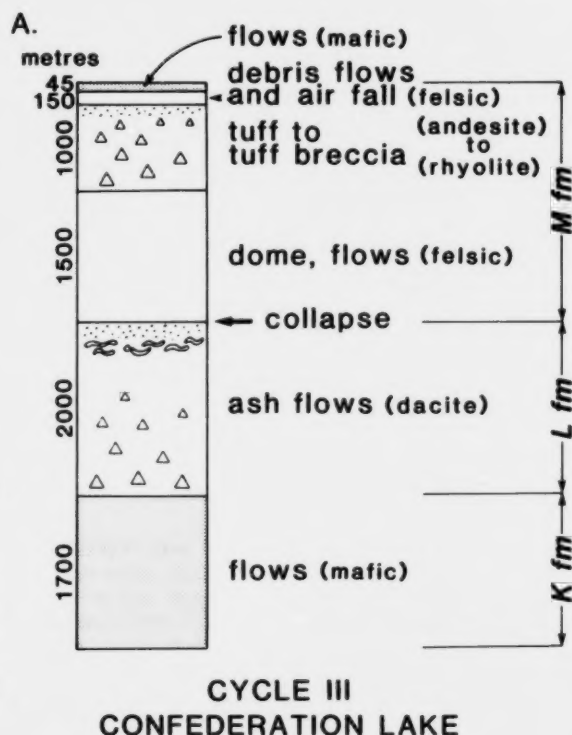


Figure 7.8. a. Schematic stratigraphic section, Cycle III, Confederation Lake. The cycle consists of a tholeiitic base, a calc-alkalic upper part with the uppermost unit being mafic tholeiitic flows.

b. A similar cycle at Flin Flon, Manitoba (after Syme *et al.* 1982).

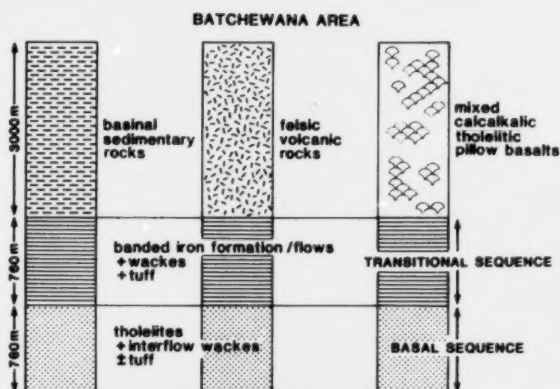


Figure 7.9. Schematic cross section of the Batchewana area based upon relations described in Grunsky (1983), with the lower tholeiitic unit overlain by calc-alkalic felsic pyroclastic rocks or clastic metasediments.

Recognition of these sequences in the field can be difficult. At Kirkland Lake, the alkalic volcanic rocks vary from being undersaturated to oversaturated, even within individual flows, however, trachytic textures and unusual colours, ranging from red to green to yellow, aid in their identification. High potassium and uranium contents in biotite-rich mafic rocks at Sunshine Lake in the Wabigoon Subprovince, give those rocks distinctive radiometric expressions.

CALC-ALKALIC BASALT-RHYOLITE

Cyclicity which results in a sequence with a compositional range from calc-alkalic basalt to rhyolite is reported to comprise the upper part (immediately below the alkalic volcanic rocks) of the super-cycles of the Abitibi Subprovince (Jensen 1984). This type of cyclicity also occurs in the Yoke Lake area of the Wabigoon Subprovince (Edwards 1984) and Figure 7.7. The main feature of this type of cyclicity is that it usually represents fractional crystallization of a basaltic parent liquid, and therefore compositional gaps are not common (Giles 1982; Giles and Hallberg 1982).

THOLEIITIC BASALT-CALC-ALKALIC FELSIC VOLCANIC ROCKS-THOLEIITIC BASALT

In this type of cycle, basal tholeiitic basalts are overlain by calc-alkalic felsic volcanic rocks ranging from andesite to rhyolite in composition. The felsic volcanic rocks range from proximal flows and domes to proximal and more distal pyroclastic rocks with intercalated sediments. The cycle is capped by tholeiitic flows. This type of stratigraphy occurs in Cycle III at Confederation Lake (Thurston and Hodder 1982 and Figure 7.8). It may also occur in parts of Cycle III in the Abitibi (Gélinas *et al.* 1984) and is known in the Proterozoic succession at Flin Flon (Syme *et al.* 1982).

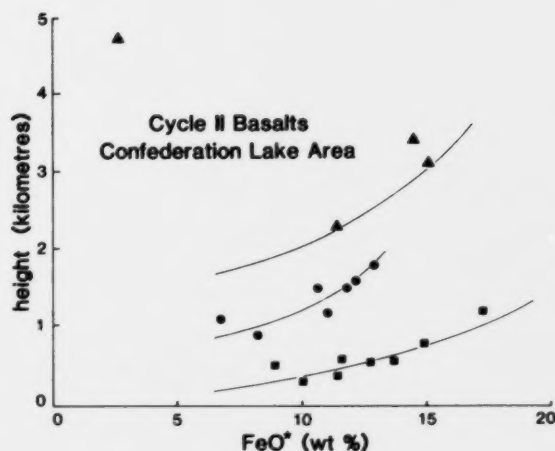


Figure 7.10. Iron enrichment cycle within the basalts of Cycle II Confederation Lake Area. Vertical axis-wt% FeO (?); horizontal axis stratigraphic height above an arbitrary datum at the base of Cycle II in the area of Narrow Lake.

This type of cyclicity has spatial and genetic association with volcanogenic copper-zinc massive sulphides (Thurston and Hodder 1982); a relationship which will be more fully described in a later section.

THOLEIITIC BASALT-METASEDIMENTS

This type of cyclicity, in which basal tholeiitic basalts with or without komatiitic units are overlain by clastic and/or chemical sediments, is of regional importance. These basalts underlie vast parts of the Superior Province. As shown in Figure 7.9, this type of cycle can be explained by the effects of regional facies variation. In the east, a basalt-sediment cycle occurs, but in the west, the cycle is a basalt-calc-alkalic felsic volcanic cycle. This is interpreted (E. Grunsky, Geologist, Ontario Geological Survey, personal communication, 1984) as a proximal volcanic environment in the west giving way eastward to a more distal sedimentary environment.

CYCLOCITY WITHIN MAJOR UNITS

As discussed above, volcanic cycles occur on varying scales, however, cyclicity of several types occurs within the various units of the cycles, that is, within mafic and felsic volcanic units.

CYCLOCITY IN MAFIC ROCKS

In basaltic sequences, Fe-enrichment cycles progressing from iron-poor units (6% to 8% FeO*) at the base to Fe rich (18% to 20% FeO*) at the top, are common. In the example shown in Figure 7.10, basalts low in the iron-enrichment cycle have 8% to 10% FeO*, increase to higher FeO* values, and are often followed by chemical or clastic sediments succeeded upward by two additional iron-enrichment cycles. Thurston and Fryer (1983) have interpreted these cycles to represent an initial mantle-derived

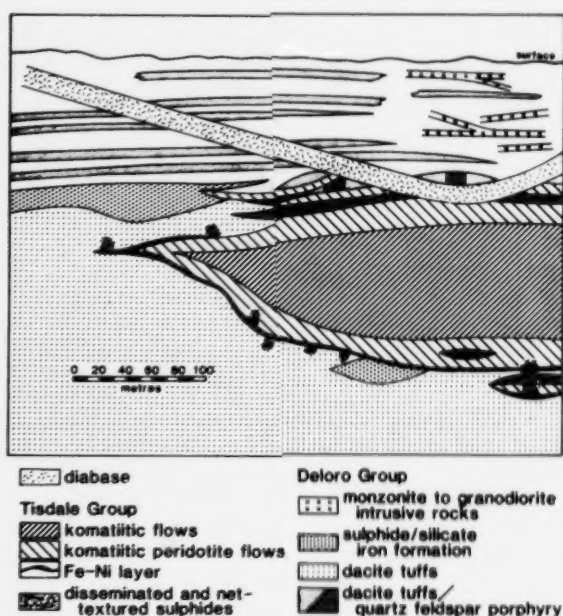


Figure 7.11. Schematic cross section of the Redstone Nickel deposit (after Robinson and Hutchinson 1982).

tholeiitic liquid which evolved by open-system crystal fractionation (O'Hara 1977) of olivine and plagioclase with late crystallization of clinopyroxene. In this type of system, the magma chamber is an open system in the sense that it is periodically refilled with batches of new magma while fractional crystallization continues.

The deposition of chemical sediments in Cycle III at Confederation Lake (Thurston 1981b) at the top of the Fe-enrichment cycles has been interpreted to mark the closing down of a magma chamber system. The chemical sediments have economic significance. At Confederation Lake, a sulphide facies iron formation in Cycle III above the lowest iron-enrichment cycle, has an above background (170 to 200 ppb) gold content (Thurston 1981b). The elevated gold content may have been derived from pervasive pre-metamorphic hydrothermal introduction of calcium. This event is marked by epidotization of the pillowed basalts. Epidotization is most intensely developed beneath the chemical sediment unit and is marked by pervasive alteration of the flows, giving way downward to epidotization concentrated around the interpillow space.

An association of gold mineralization occurs at Red Lake and Confederation Lake with high Fe basalts (Pirie 1981; Thurston 1982). The gold mineralization is generally associated with late vein systems (McGeehan and Hodgson 1981). If gold is at least in part transported by the thio complex (HS^-), then the above spatial association may mean gold is in part fixed by pyrite-forming reactions in iron-rich rocks.

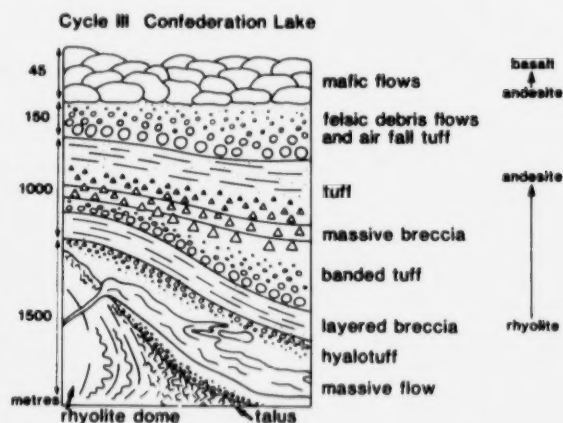


Figure 7.12. Compositional zonation within the upper felsic part of Cycle III, Confederation Lake. In a regional sense, this unit is the upper felsic part of the cycle, however, note that the upper unit changes gradationally from rhyolite to andesite bulk composition. The diagram consists of proximal facies on the left and more distal units on the right.

Cyclicity in komatiites has been little studied, but Arndt (1978) has noted the association of komatiite-hosted Ni deposits with the high-MgO parts of komatiite units (Figure 7.11) in Ontario and Western Australia. Beyond a general spatial association with high MgO-komatiites, no particular type of komatiite unit appears to be favoured as the locus for nickel mineralization. The ores occur in the basal part of individual flows, and most authors suggest the nickel sulphides occur there as a result of sulphide droplets settling out of the silicate magma due to immiscibility.

Robinson and Hutchinson (1982) ascribe a volcanogenic-exhalative origin to the Redstone nickel deposit south of Timmins. The deposit of nickel sulphides occurs above a calc-alkalic dacite tuff as massive iron-nickel sulphides which grade along strike into sulphide facies iron formation. This unit, interpreted to be composed of chemical metasediments, is capped by komatiitic flows. In terms of cyclical volcanism, then, the deposit occurs at a stratigraphic level representing a volcanic hiatus. The deposit originated by hydrothermal fluids circulating through underlying komatiites and depositing Ni sulphides at the rock-water interface.

CYCLICITY IN FELSIC SEQUENCES

Cyclicity in felsic volcanic sequences occurs on scales ranging from the macro (10^3 m) through the meso scale (10^2 m) to the micro scale (m to cm). Only selected examples of each type will be described.

Mega-Scale Cycles

At Confederation Lake Cycle III, the youngest cycle, can be subdivided (Figure 7.12) into a mafic base

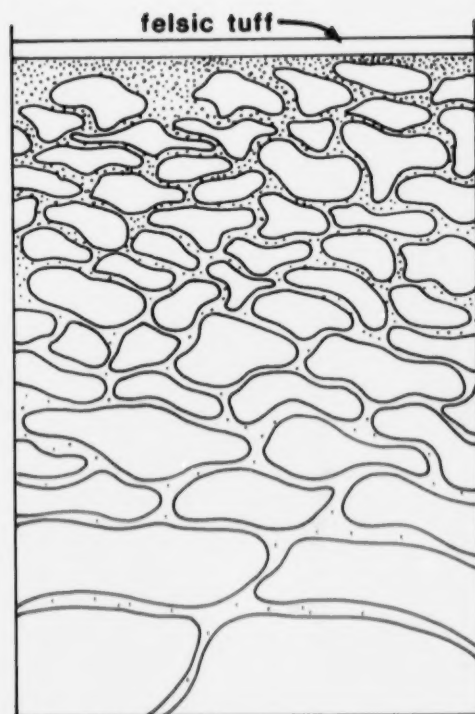


Figure 7.13. Schematic cross section of an individual mafic flow at the Maybrun Mine with large pillows at the base of the flow, small pillows toward the top, and fine-grained tuff at the top (after Setterfield *et al.* 1983).

(formation K) above which are dacitic pyroclastic rocks of formation L and formation M, a rhyolitic dome, and correlative flows and pyroclastic rocks. In a regional sense, formations L and M together form the felsic upper part of Cycle III. However, formation L is composed of dacitic lapilli-tuff to tuff-breccia with abundant shards, and broken phenocrysts. Also, some evidence of welding which led Thurston (1981b) to interpret it as an ash-flow is present in this formation. Formation M (above formation L) is interpreted to be composed of dome-related flows and less extensive pyroclastic units than in formation L. These rocks accumulated in a fault-bounded trough. Violent, extensive eruption of ash-flows (formation L), followed by dome-related siliceous volcanism, has been interpreted as a Plinian eruption followed by caldera collapse; namely, formation of a sector graben occurred. This represents major scale cyclicity of volcanic processes and products. In younger terrains, this type of cyclicity has been explained in terms of the caldera cycle (Smith and Bailey 1968; Smith 1979). Other Precambrian examples are at Noranda (Dimroth *et al.* 1982), the Setting Net Lake area (Ayres 1977), and Flin Flon, Manitoba (Syme *et al.* 1982).

Meso-Scale Cyclicity

Formation M is the uppermost unit of Cycle III at Confederation Lake. The formation consists of a rhyolitic endogeneous dome with lenticular deposits of collapse debris and about 1500 m of overlying felsic flows. These flows are succeeded by 1000 m of felsic tuff-breccia to lapilli-tuff which grades gradually to an andesitic composition. This is followed by 150 m of felsic debris flows, air-fall tuffs, and 45 m of pillowed mafic flows (Figure 7.12). The cyclicity within this sequence is two fold: 1) eruption type and products and 2) compositional cyclicity. The sequence progresses from quiescent extrusion of flows through violent eruption of coarse pyroclastic rocks to quiescent eruption of mafic flows. Compositionally, this 1000 m thick sequence grades from rhyolite at the base to andesite at the top. In the area of southern Fly Lake (Thurston 1981b), a single depositional unit of ash-flow contains predominantly essential fragments of dacite with some rhyolite fragments at the base and andesite fragments at the top (Thurston and Hodder 1982). This single compositionally zoned unit and the overall compositional zonation of formation M have been ascribed by Thurston and Hodder (1982) to eruption from a compositionally zoned magma chamber.

Micro-Scale Cyclicity

Ash-flows ranging in thickness from 1 to 5 m occur in formation M at Confederation Lake (Thurston and Hodder 1982). These rocks are poorly bedded lapilli-tuff to tuff units displaying normal density and reverse size grading of ash, pumice, and lithic fragments. The clast-types, geometry, and vertical sequence of primary structures (compare Sparks *et al.* 1973, Figure 7.13) suggest an ash-flow origin (Thurston 1981b). The concentrations of pumice have been flattened, extensively silicified, and epidotized during vapour-phase recrystallization shortly after deposition. The mobility of sulphides is economically significant in this regime. Pyrite has partly replaced pumice fragments at the top of each thin ash-flow depositional unit, creating areas of pyrite, minor pyrrhotite, and traces of sphalerite forming up to 30% to 40% of the rocks over thicknesses of 15 cm. This phenomenon produced anomalous geophysical response (Assessment Files Research Office, Ontario Geological Survey, Toronto) which was subsequently drilled. This type of sulphide occurrence, however, has limited economic potential.

HIATUSES

Stratigraphic hiatuses in volcanic sequences are often marked by interflow units of clastic sediment, chemical sediment, or fine-grained distal facies tuffs. By virtue of their generally fine grain size, interflow units can form the impermeable cap of Hodgson and Lydon (1977) beneath which hydrothermal activity produces mineral deposits at scales ranging from single depositional units to meso-scale cycles.

NORTH POLE BARITE

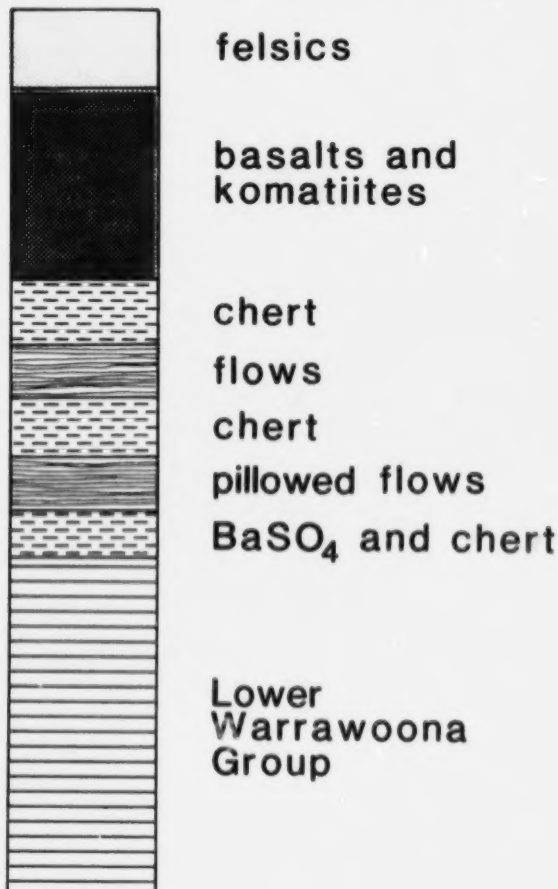


Figure 7.14a. Schematic cross section of barite-bearing units in the North Pole area, Pilbara Block, Western Australia (after Hickman *et al.* 1980).

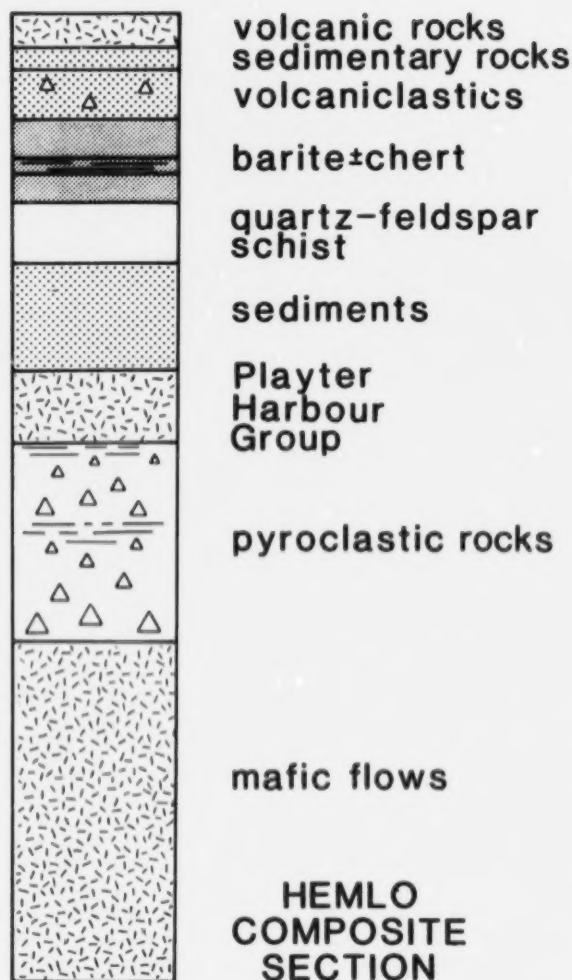


Figure 7.14b. Schematic cross section of the Hemlo area (after Muir 1982 and Patterson 1984).

DEPOSITIONAL UNIT SCALE

At the Maybrun Mine south of Kenora, Setterfield *et al.* (1983) described mafic flows with minor interflow cherty tuffs or zones of collapsed pillows sealing the top of individual flows. Copper-gold mineralization is preferentially concentrated toward the top of individual flows because interpillow space increases upward in each flow as pillows become smaller and more loosely packed (see Figure 7.13).

FE-ENRICHMENT CYCLE SCALE

We noted earlier that gold deposits at Red Lake, Timmins, and Western Australia (Groves and Gee 1980) tend to be spatially associated with the iron-rich top of tholeiitic sequences, the iron-rich basalts are often overlain by auriferous chemical sediments, usually ironstone. A non-economic example is the

Bobjo Prospect where sulphide facies ironstone overlies variolitic iron-rich basalt in Formation K of Cycle III at Confederation Lake. There, Thurston (1982) described the presence of above background (170 to 200 ppb) levels of gold in chemical sediments above hydrothermally altered, epidotized tholeiitic basalts.

Hydrothermal alteration with substantial seawater input is involved in the production of sedimentary barite in South Africa (Heinrichs and Reimer 1977) and Australia (Hickman *et al.* 1980) (Figure 7.14a). These Archean barite occurrences represent both veins and barite-rich sedimentation during a hiatus in volcanism. Given the fact that barium and gold are spatially associated, and the fact that the major source of barium is seawater (Heinrichs and Reimer 1977), and the major source of gold is the surrounding volcanic rocks (Fyfe and Kerrich 1984), a hydrothermal system is probably the source of this

Confederation Lake Area

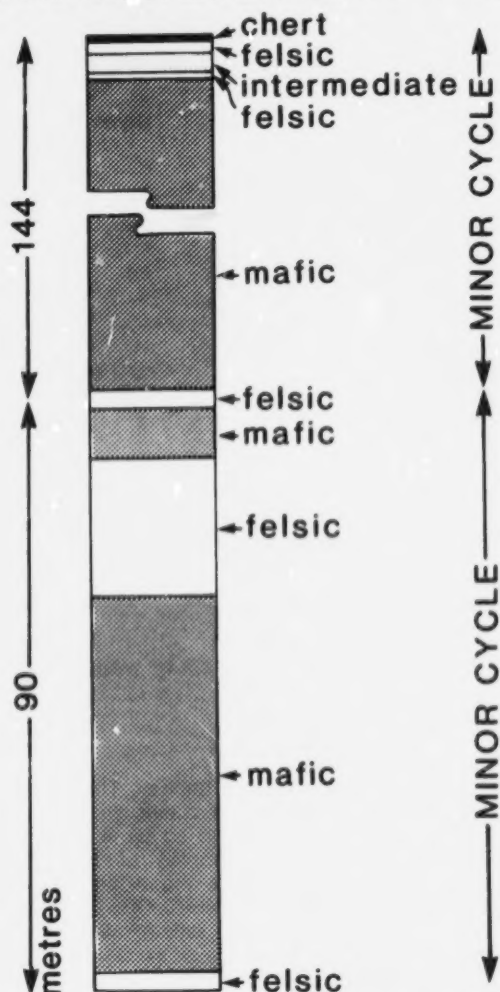


Figure 7.15. Minor scale cycles within the upper part of Cycle II Confederation Lake. This is a generalized overview to permit an appreciation of the gross features of this scale of cyclicity. Please see Figure 7.1 for greater detail.

mineralization type. The accumulation of gold in chemical sediments such as barite in some occurrences (Heinrichs and Reimer 1977) suggests that perhaps the barium-gold mineralization at Hemlo (Patterson 1984) may be related to a hiatus in volcanism (Figure 7.14b). This very premature suggestion is subject to verification in the field.

Chert fragment-rich conglomerates with angular chert fragments occur above the basalt in the Phinney-Dash Lakes area (Edwards and Hodder 1981). These authors suggest the chert represents chemical sedimentation during a hiatus in basaltic volcanism. Brecciation and slumping of the chert to form the conglomerate was produced by hydrother-

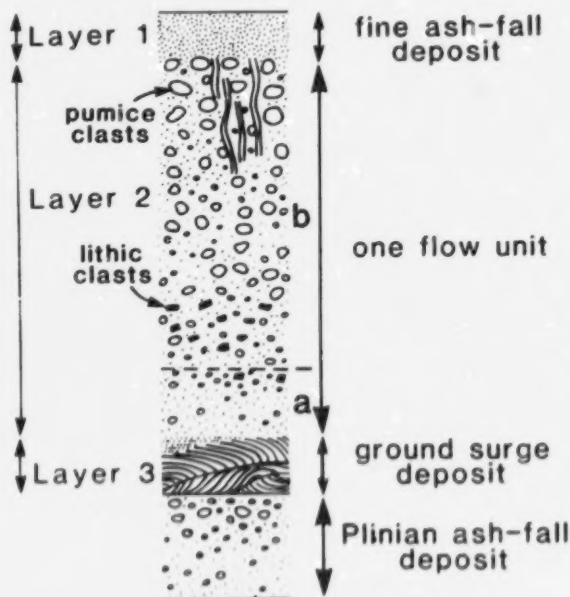


Figure 7.16. Schematic cross section of a typical ash-flow (after Sparks et al. 1973). Layer 1 consists of crossbedded tufts of base surge origin. Layer 2 is lapilli-tuff to tuff-breccia, poorly sorted, showing reverse size grading, that is, concentration of pumice fragments in the upper part and normal density grading with denser lithic fragments toward the base. This unit is produced by gravitational collapse of the eruption column. Layer 3 is poorly sorted, poorly and generally thin bedded tuff deposited from the ash cloud.

mal activity beneath the impermeable chert cap leading to steam-driven brecciation of the chert. Gold prospects are associated with this unit (Edwards and Hodder 1981).

Minor scale chemical cycles in volcanism are important in Au deposition at the Hill-Sloan-Tivey quartz horizon east of Confederation Lake (Thurston 1982). Four minor cycles, each above 150 m thick, occur in Cycle II. These cycles consist of basal basaltic andesites overlain by rhyolite and chemical sediment (Figure 7.15). The chemical sediment units represent hiatuses in volcanism, terminating some of the minor scale cycles. Based upon chemical evidence, Thurston and Fryer (1983) suggested these cycles were the product of eruption from a chemically zoned magma chamber. Gold mineralization occurs in the chemical sediments at the top of one of the minor cycles (Thurston 1982) and in vein systems cutting these units.

HIATUSES IN FELSIC SEQUENCES

Hiatuses in felsic volcanism may be produced by the catastrophic emptying of the magma chamber during a Plinian eruption, that is the production of ignim-

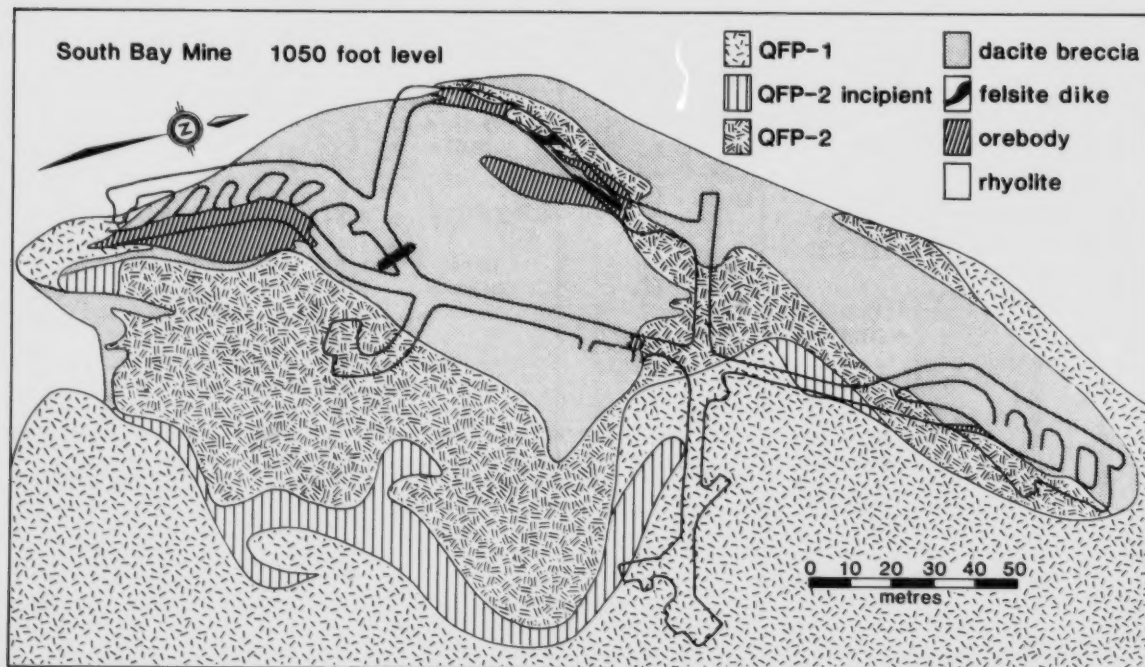


Figure 7.17. Cycle III Confederation Lake-schematic cross section of the Selco Cu-Zn-Ag orebody (after Thurston *et al.* 1978).

brites. A cross section of a typical ignimbrite is shown in Figure 7.16.

As described above, the top of formation L in Cycle III at Confederation Lake marks the cessation of Plinian eruptive activity and the onset of caldera collapse. The collapse is the sagging of the magma chamber roof which may founder piecemeal or as a unit. The cause of the collapse is the catastrophic emptying of the magma chamber. This is represented in stratigraphic terms by a hiatus in volcanism, where small scale hydrothermal activity may occur by analogy with similar systems in younger terrain (Cruson and Pansze 1983). The lack of large scale hydrothermal activity at this stratigraphic level at Confederation Lake, for example, has been noted by Sopuck (1977).

The hiatus in felsic volcanic activity marked by the contact between the endogeneous quartz-feldspar porphyry dome and associated dome-collapse talus deposits (Pollock *et al.* 1970; Thurston 1981b) is the site of the South Bay copper-zinc-gold volcanogenic massive sulphide deposit (Figure 7.17). Following the conventional model for volcanogenic massive sulphide genesis (Franklin *et al.* 1981), the mineralizing hydrothermal activity took place during a hiatus in volcanism.

MAGMA CLAN TRANSITIONS

As shown in the above survey of chemical types of volcanic cyclicity, there are ample opportunities for development of depositional hiatuses during the tran-

sition from one magma clan to another. This provides the opportunity for chemical or clastic sedimentation of marble, barite, ironstone, and so on, with or without gold mineralization. Examples of mineralized magma clan transition include the Adams Mine, a komatiitic tholeiite transition (MERQ/OGS 1984), and the Sherman Mine, a tholeiite calc-alkalic transition (Bennett 1978). Both are iron deposits. Gold occurs at the tholeiite-calc-alkalic transition in Cycle II at Confederation Lake (Thurston 1982). The location of ironstone and massive sulphide bodies toward the top of the Cycle II calc-alkaline sequence in the Abitibi Subprovince (MERQ/OGS 1984; Pyke and Middleton 1970) are basically controlled by the transition from calc-alkalic volcanism of Cycle II to the komatiitic volcanism which begins Cycle III.

THE CALDERA CYCLE

This section describes the application of conceptual models developed for modern volcanic rocks to Archean sequences. This is done to show that Archean volcanism does not differ substantially from Phanerozoic analogues and, more importantly, that these conceptual models may be used to predict the place of mineralization in Archean sequences. Examples of this type of analysis for the Confederation Lake area are described in detail, herein.

The complexities of volcano evolution from quiescent eruptions to large-scale violent Plinian eruptions, caldera formation, and renewed volcanism are all part of a logical, connected series of events, the

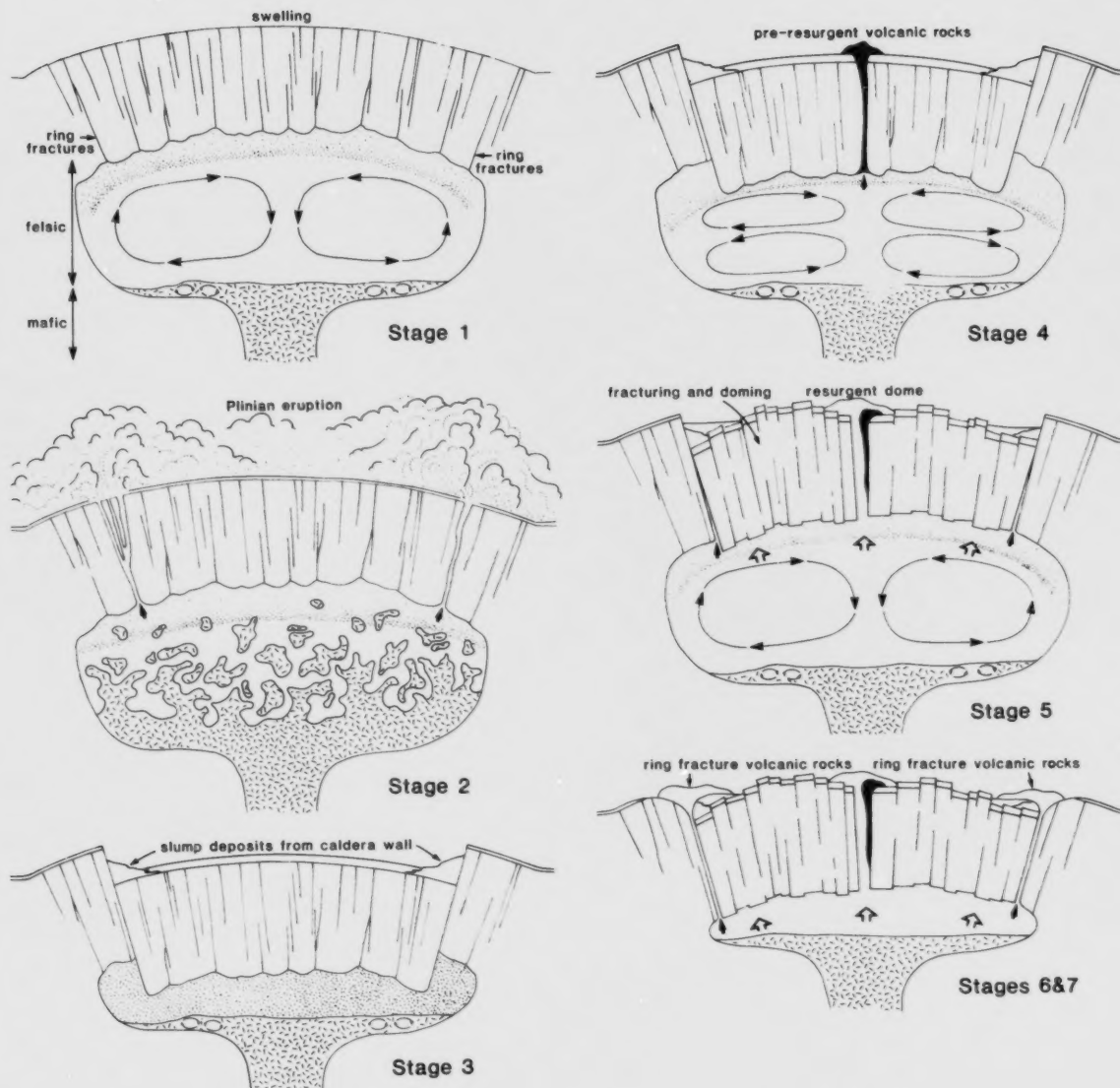


Figure 7.18. The Caldera cycle (after Smith and Bailey 1968). The numbers refer to stages in the Caldera cycle explained in the text.

caldera cycle (Figure 7.18). The caldera cycle was developed by Smith and Bailey (1968) to unify these apparently disparate events into an organized concept. Their work was based upon the series of events at the Valles caldera in the U.S.A., and has the following seven stages:

1. *regional tumescence and generation of ring fractures*

The area of tumescence is generally larger than the outer ring fractures of a given cauldron.

2. *caldera forming eruptions*

The caldera "a circular volcanic depression, more or less circular or cirque-like in form" (Williams 1941) is produced by the collapse of the roof of the magma chamber upon the catastrophic emptying of the chamber at eruption. The eruptions are Plinian; produced by the explosive frothing and disintegration of magma by internally produced gas bubbles (Sparks 1978). This explosive fragmentation produces a large eruption column with a vertical extent of 30 to 50 km, a high degree of fragmentation, and dispersal of the products (Walker 1973). This stage is represented by formation I at Confederation Lake.

3. *caldera collapse*

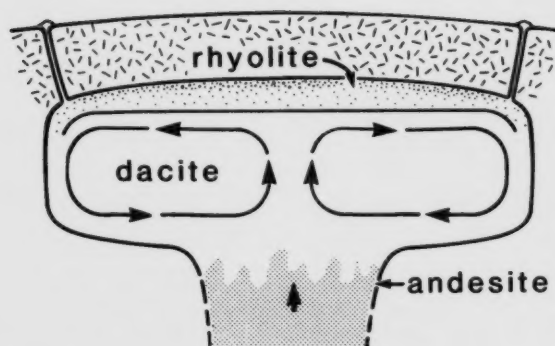


Figure 7.19. Schematic cross section of a compositionally zoned magma chamber (after Hildreth 1979). The chamber is Si, LIL element (Rare Earths and so on) and volatile rich at the top and phenocryst poor. Silicon content, LIL elements, and volatiles decrease and phenocrysts become more abundant downward. The chamber is heated by periodic intrusion of mantle derived basalt.

The catastrophic emptying of the magma chamber leads to piecemeal or monolithic collapse of the magma chamber roof. The collapse allows the caldera to fill with the products of Stage II above, giving rise to the notion of an intracaldera ignimbrite (Lipman 1976) trapped within the topographic wall of the caldera usually volumetrically dominant, and an outflow facies, the smaller part, which spills out of the caldera. This stage is marked by the intrusion of granitic sills at Confederation Lake (Thurston (1981).

4. preresurgence volcanism and sedimentation

This stage chiefly involves infilling of the caldera with debris from the caldera walls by caving, avalanches, and gravity sliding. Volcanism is relatively uncommon, but is found in the Creede caldera. Lake beds are often found with calderas (for example, Hildebrand 1982). This stage has not been recorded at Confederation Lake.

5. resurgent doming

This stage involves topographic doming within the caldera as the magma chamber re-inflates. A variety of types of grabens, with dips up to 65° are produced by the doming. The question of the causes of resurgence and associated doming was addressed by Marsh (1981). He feels that in a theoretical analysis, regional detumescence, the sinking of the regional surface after inflation prior to the first eruption, is favoured because it produces the observed time lag of about 10⁵ years between caldera initiation and resurgence.

6. major ring-fracture volcanism

This stage involves volcanism from the moat or ring-fracture and the products are often intercalated with sediments from Stage IV above. This stage often completely fills the caldera. At this stage, about 800 000 years from caldera initiation will have elapsed. This stage is represented in several areas by post-

collapse volcanic domes and associated extrusives (Thurston 1981).

7. terminal solfataric and hot-spring activity

This stage, when present, is due to the incomplete evacuation of the magma chamber. The remaining magma freezes in place, but the gradual loss of heat is accomplished by conduction by hydrothermal fluids which: 1) alter surrounding volcanic rocks; 2) are responsible for leaching of copper, zinc and so on from their surroundings and deposition in cooler areas as volcanogenic massive sulphide deposits. The hydrothermal activity of Stage VII does not occur during Stages III to V of the caldera cycle because the magma chamber has been catastrophically emptied during Stage II, hence, there is no magma available which needs to lose heat by conduction through flow by hydrothermal fluids and no source of halogens to increase the efficiency of the metal-leaching process. This stage is represented by volcanogenic copper-zinc sulphide deposits in several Superior Province greenstone belts.

ZONED MAGMA CHAMBERS

Within the Caldera Cycle model provided by Smith and Bailey (1968), more recent work (Hildreth 1979, 1981; Smith 1979) has shown that many ignimbrite-producing magma chambers are chemically zoned (Figure 7.19). These chambers are large, with a dominant volume of rhyolitic magma forming the upper part of the chamber. The rhyolite is underlain successively by dacitic, andesitic, and basaltic liquid. Episodic addition of mantle-derived basalt to the base of the chamber supplies heat to keep the upper part liquid. Convection occurs throughout the chamber (McBirney and Noyes 1976), and some combination of convection, a slow process in viscous felsic melts, and volatile streaming is active in the upper rhyolitic part of the chamber. In a major element sense, this upper part is rhyolitic; however, Hildreth (1979) described large trace element concentration gradients within melts of essentially constant major element composition.

Commonly, these chambers are catastrophically emptied during Plinian eruptions (Smith 1979). This may occur when the arrival of a fresh batch of basaltic magma at the base of the chamber saturates the felsic part of the system in volatiles which triggers the eruption (Sparks *et al.* 1977). Alternatively, the small convective cells present in a compositionally zoned chamber may rapidly roll over (Rice 1981; Huppert *et al.* 1982). This process can occur (Huppert *et al.* 1982) when the specific gravities of the basaltic and overlying rhyolitic magmas become equal. This can come about through the fractionation of mafic minerals of high specific gravity from the basalt. This has two effects. It immediately makes the basaltic magma lighter, and renders the magma supersaturated in volatiles, causing vesiculation which again decreases its specific gravity.

Thurston and Hodder (1982) have analyzed the development of Archean stratigraphy at Confederation Lake in terms of a model involving the tapping of a compositionally zoned magma chamber during resurgent volcanism (Stage VI of Smith and Bailey 1968). Observations fitting the model include:

1. a progressive decrease in SiO_2 with stratigraphic height within Cycle III
2. a decrease of SiO_2 with stratigraphic height in individual ignimbrite depositional units
3. crossing rare earth elements patterns related to the heavy rare earth element enriched character of the top of the Cycle III magma chamber similar to that found in younger, compositionally zoned chambers

Thurston and Hodder's (1982) analysis indicates that Cycle III of Confederation Lake represents caldera collapse and resurgent magmatism developed from a compositionally zoned magma chamber. These authors suggest both features are present in many copper-zinc mineralized successions. Further analysis showed (Thurston *et al.* 1984) that rhyolites involved in development of copper-zinc deposits are produced by contamination of felsic magma with large volumes of silicic crust. The crust provides the abundant fluorine and other volatiles needed for metal transport.

APPLICATIONS TO EXPLORATION

The stratigraphy of Cycle III at Confederation Lake has been analyzed in terms of resurgent volcanisms in a caldera cycle model involving a compositionally zoned magma chamber. The question is whether this problem is repeated elsewhere and whether there is a pattern with application to exploration. Some intriguing possibilities exist.

The stratigraphy of Noranda has been analyzed in terms of a caldera collapse (de Rosen-Spence 1976). Gibson has demonstrated (Gibson *et al.* 1983) that post-collapse volcanism is directly related to copper-zinc deposits. Composite dikes mapped by Gibson (Geologist, Falconbridge Copper, personal communication, 1983) include xenoliths of partly melted granitic rocks, showing directly the involvement of melted sial in petrogenesis. This scenario is also borne out by analysis of trace element geochemistry (Gélinas and Ludden 1984).

Caldera collapse is described in the Setting Net Lake area (Ayres 1977), where alteration within the caldera sequence is widespread (L.D. Ayres, Professor, University of Manitoba, personal communication, 1980). Lead-rich vein deposits occur within the caldera sequence (Adams 1976).

Stratigraphic and volcanologic analysis of other Archean terrains should yield similar histories of volcanological processes in that collapse often follows large ignimbrite eruptions. In fact, Thurston *et al.* (1985) suggested that ignimbrite eruptions were the dominant style of Archean felsic volcanism. The compositionally zoned nature of many Archean felsic successions is shown by a unique trace element geochemical signature (Campbell *et al.* 1984) which Thurston *et al.* (1985) maintained was the result of compositionally zoned magma chambers.

SUMMARY

In this paper, it is noted that a knowledge of stratigraphic position in particular types of volcanic cycles is essential. A model of the volcano's behaviour can

be developed which is based upon stratigraphic successions such as ash-flows (Plinian) followed by domes, flows, and small-scale ash flows. These models involve caldera collapse after ash-flow eruptions, re-inflation of a compositionally zoned chamber, and resurgent volcanism. This pattern of collapse and resurgence occurs around a compositionally zoned chamber as evidenced by the major and trace element variation patterns and stratigraphic characteristics.

An understanding of these processes and cyclicity on a variety of scales permits the geologist to predict more confidently probable sites of mineralization. This, of course, does not avoid the necessity for conventional exploration procedures. It simply provides a new means of evaluating the mineral potential of large tracts of "greenstone" successions.

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Chapter 8

Recognition of Alteration in Volcanic Rocks Using Statistical Analysis of Lithogeochemical Data

E.C. Grunsky

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ABSTRACT

A statistical study of the lithogeochemistry of the volcanic rocks in the Ben Nevis area of Ontario has shown that spatial presentation combined with correspondence analysis and dynamic cluster analysis can be used to delineate stratigraphy as well as alteration zones characterized by carbonatization and sulphur enrichment. An extensive zone of carbonatized volcanic rocks surrounds a zone of mineralization in this area.

Correspondence analysis calculates factors which explain the distribution of data with respect to the variation patterns that are represented by the chemical component abundances. In the case of the Ben Nevis data, when major oxides are used, the first and most significant factor describes the compositional variation in the original igneous trend (fractionation trend); the second factor characterizes the compositional variation due to the process of carbonatization; the third factor indicates compositional variation in the form of sulphur enrichment associated with mineralization. The use of major oxides combined with trace elements produces similar results.

Dynamic cluster analysis groups together samples that have been affected by similar processes. Groups related to fractionation trends can be clearly distinguished from groups that have undergone alteration processes.

When properly applied and interpreted, these statistical techniques can assist in mineral exploration.

INTRODUCTION

Volcanic rocks are commonly host to several types of mineral deposits such as massive sulphide deposits (Sangster and Scott 1976) and epithermal deposits (Rose and Burt 1979). Alteration is associated with these deposits and is discernible in the form of mineralogical, textural, and chemical changes due to the circulation of hydrothermal fluids. Most deposits are surrounded by haloes of alteration defined by anomalous chemical abundances; these zones are spatially much larger than the ore deposits themselves and form significant exploration targets. The use of lithogeochemistry can be instrumental in detecting these alteration zones if statistical techniques are used effectively to recognize patterns of alteration within sample populations.

A lithogeochemical study was carried out by the Ontario Geological Survey in the Ben Nevis Township area, Ontario (Figure 8.1), in which zones of alteration associated with mineralized occurrences (Figure 8.2) were identified using the technique of correspondence analysis combined with dynamic cluster analysis. A previous study by Wolfe (1977) in the same area outlined a zone of zinc enrichment related to a dispersion halo which Wolfe attributed to an alteration pipe associated with the formation of volcanogenic massive sulphide deposits.

Locally, the two most significant mineral occurrences are the Canagau Mines Deposit and the Crox-all Property. Detailed property and deposit descriptions can be found in Jensen (1975).

The Canagau Mines Deposit is underlain by strongly carbonatized, sericitized, and silicified mafic and felsic volcanic rocks. Mineralization consists of galena, sphalerite, gold, silver, and pyrite within east-

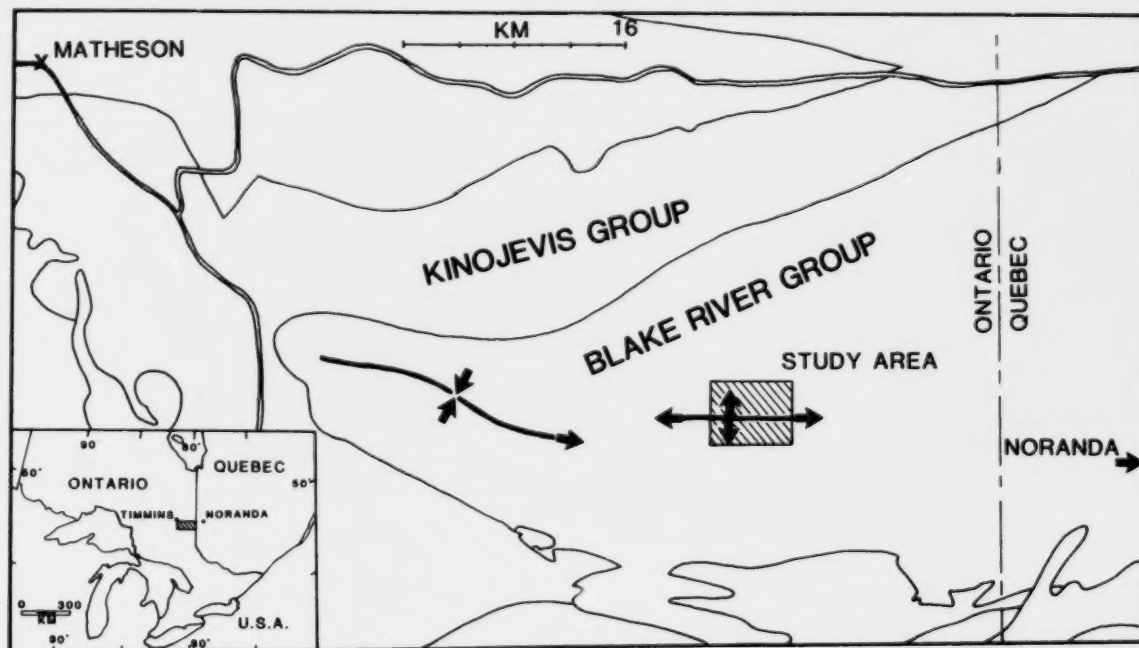


Figure 8.1. Location map.

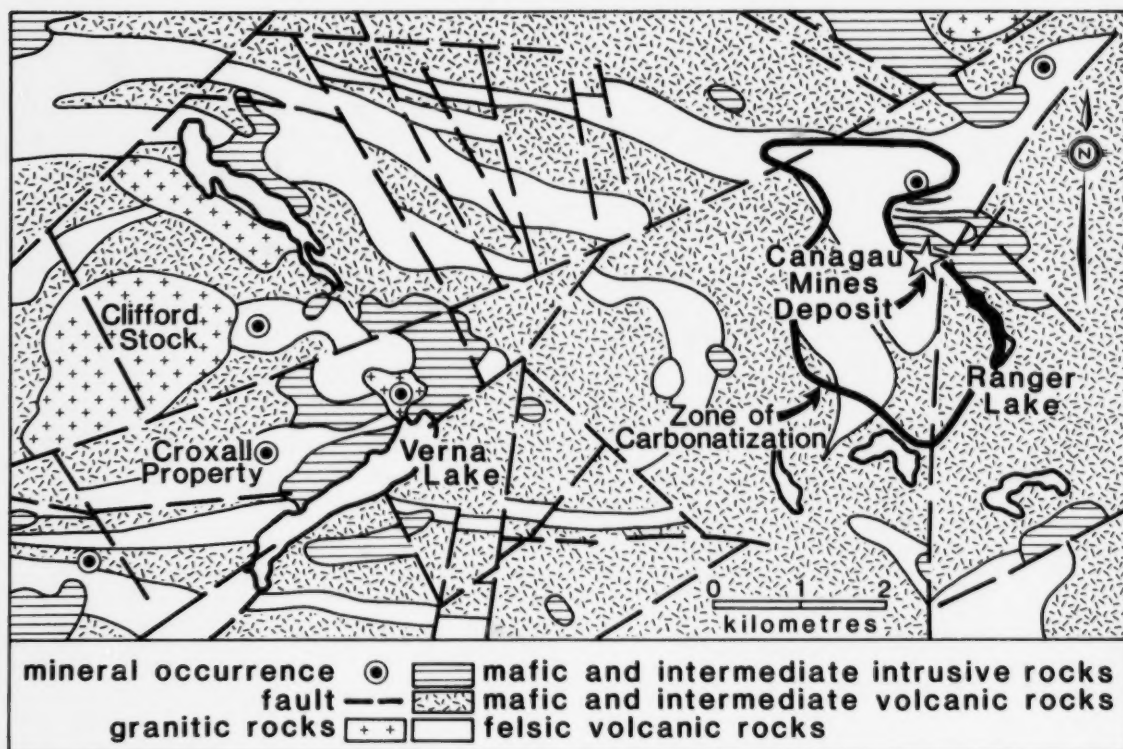


Figure 8.2. Geology of the Ben Nevis area.

trending fractures and shear zones that dip 40° to 60° toward the south. Grades and tonnages are unknown, but the deposit is not currently considered to be economic.

The Croxall Property consists of a zone of brecciated and sheared rhyolite with interstitial pyrite, chalcopryite, chlorite, calcite, and quartz. Gold assays have been reported up to 0.04 ounce per ton.

GEOLOGY OF THE BEN NEVIS TOWNSHIP AREA

The Archean volcanic rocks of the Ben Nevis area comprise the top of the Blake River Group within the Abitibi volcanic-sedimentary belt in Ontario. This group is exposed in a broad east-trending synclorium from south of the Matheson area in Ontario eastward to the Noranda area of Quebec (see Figure 8.1). The area has been mapped in detail by Jensen (1975; Figure 8.2) and is underlain by volcanic rocks of calc-alkalic affinity (Figure 8.3). The most common volcanic rocks are basaltic pillowed flows, pillow breccias, and breccias.

Many of these volcanic rocks appear to be amygdaloidal, with vesicles varying in amounts from $<1\%$ to $>60\%$, and with a size range of 1 mm to 3 cm across. Such vesicularity provides the porosity for the circulation of hydrothermal fluids. In some areas, many of the larger amygdules (>5 mm) are con-

nected by planar stringers of quartz and/or carbonate <1 mm across. These stringers probably represent a microfracture system that increased the permeability of the rocks and controlled the circulation of fluids. Many zones of large amygdules cut across pillows

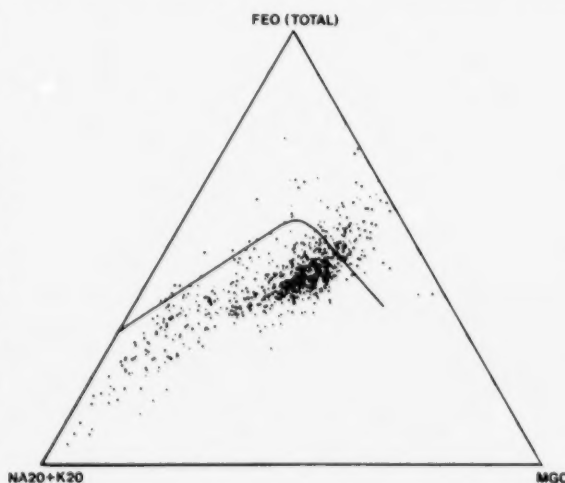


Figure 8.3. AFM diagram of the Ben Nevis area. Note the calc-alkalic trend.

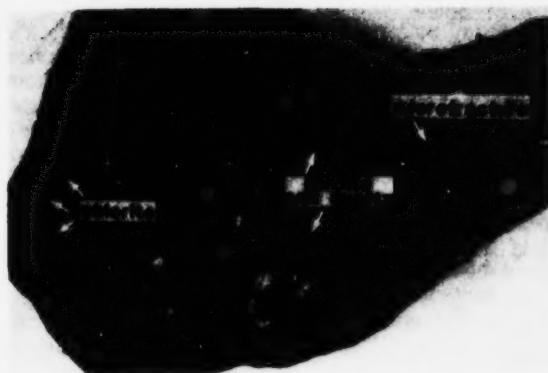


Photo 8.1. Carbonate, quartz, and chlorite amygdulites in a pillowed basalt. The larger "ovoids" are interconnected by quartz-carbonate filled microfractures and may be secondary in origin.

and pillow selvages. This would suggest a secondary origin. Macdonald (1983) suggested that "ovoids" in mafic volcanic flows, that are commonly mistakenly identified as amygdulites, are possibly due to secondary effects related to alteration. It seems probable, therefore, that many of the larger quartz-carbonate ovoids that are connected by microfractures are secondary in origin and related to the development of the alteration zone.

Two major felsic volcanic units consisting of rhyolitic and dacitic tuff, tuff-breccia, and flows occur within the predominantly mafic volcanic sequence. The volcanic environment in the Ben Nevis area is interpreted as proximal, with a volcanic centre occurring in the vicinity of the Clifford Stock. The volcanic sequence is intruded by gabbroic and dioritic bodies of tholeiitic affinity (Figure 8.3) and is folded into a domical anticlinal structure within the larger Blake River Synclinorium (see Figure 8.1).

The area is intersected by several faults that are believed to be related to volcanic activity and later doming of the sequence. A major north-trending fault in the eastern part of Ben Nevis Township is part of a regional lineament that transects the Blake River Group. This fault may be a deep seated structure; a possible conduit for hydrothermal fluids that passed through the eastern part of the Ben Nevis area.

ALTERATION

Rocks of the Ben Nevis area have been metamorphosed under conditions of burial metamorphism and are represented by zeolite facies and prehnite-pumpellyite facies (Jensen 1975). Around the felsic intrusions, the metamorphic grade is albite-epidote hornfels facies.

Through the Ben Nevis area, chlorite is a common constituent in the amygdulites and in the groundmass of the mafic to intermediate volcanic rocks. The origin of the chlorite is probably due to the interaction of CO_2 -rich hydrothermal fluids with the host rock and the resultant destabilization of Ca and the resultant assemblage of chlorite and/or albite (Michel

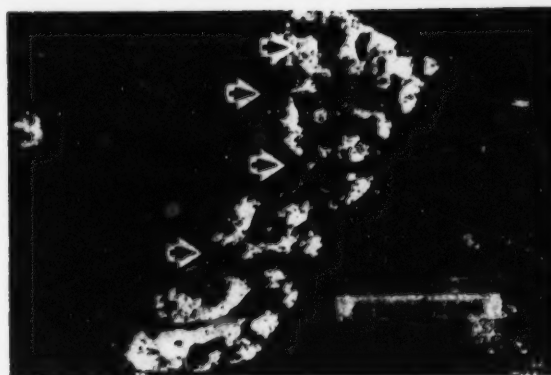


Photo 8.2. Replacement of calcium-rich plagioclase phenocryst by calcite. Groundmass contains fine-grained calcite and dolomite.

Mellinger, Research Scientist, Saskatchewan Research Council, personal communication, 1985). Petrographic studies have shown the presence of saussurite that formed from the breakdown of plagioclase. Saussurite occurs throughout the mafic to intermediate volcanic sequence where CO_2 phases were not present (Michel Mellinger, Research Scientist, Saskatchewan Research Council, personal communication, 1985). Sericite is also present in both the mafic to intermediate volcanic rocks and the felsic volcanic rocks. Its presence within the felsic volcanic rocks may be explained by the breakdown of orthoclase, albite, and other potassium-bearing minerals during metamorphism; however, the sericite within the mafic to intermediate volcanic rocks suggests that fluids enriched in potassium passed through these rocks causing alteration.

In the field, the most obvious form of alteration is pervasive carbonatization (Photo 8.1). The bleached appearance and deep weathering rind typical of these rocks allow for easy visual identification.

Intense pervasive silicification occurs only in the Canagau Mines Deposit. Within the main zone of pervasive carbonatization, the quartz-carbonate ovoids are much less abundant. Ovoids that do occur contain only carbonate. This may be due to replacement of quartz by calcite. Alternatively, quartz could have formed only away from the main centre of carbonate alteration where different temperature or chemical conditions prevailed.

In thin section, the carbonate occurs as large anhedral patches in the matrix of mafic flows (Photo 8.2). Pervasive replacement of the matrix is most widespread close to the north-trending fracture in the eastern part of Ben Nevis Township. X-ray diffraction studies of the carbonate indicate that the dominant phase is calcite with only trace amounts of magnesite, dolomite, ankerite, and siderite (Geoscience Laboratories, Ontario Geological Survey, Toronto). Dolomite was noted to be more common in the matrix than in the ovoids or amygdulites. Thin section studies indicate that the carbonate commonly formed through replacement of plagioclase; thus, it appears that calcium was not added to the system, but was recombined with externally derived CO_2 . Other evidence, that will be presented below, suggests that calcium

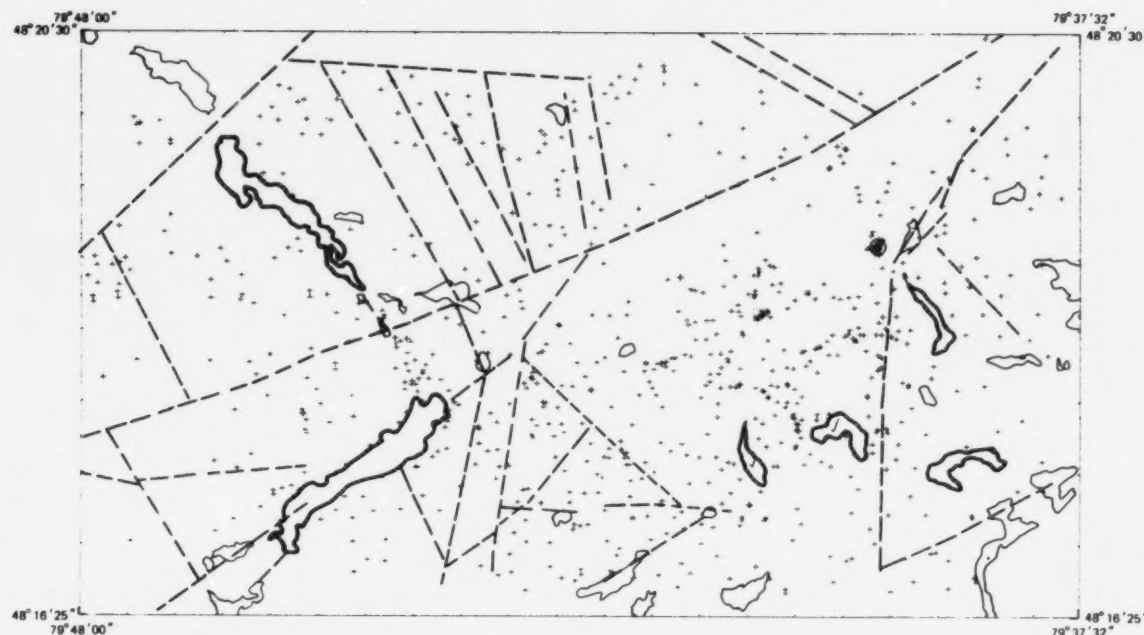


Figure 8.4. Distribution of samples in the Ben Nevis area.

was removed from the main centre of carbonatization.

Away from the main zone of carbonatization, the pervasive carbonate alteration decreases, and there is an increase in carbonate and silica flooding (Photo 8.2). The flooding commonly takes the form of amygdule or "ovoid" fillings and interconnecting microfractures filled with quartz and/or calcite. The increase of flooding and decrease of pervasive alteration may reflect a temperature gradient in the alteration zone. Textural relationships within quartz-rich ovoids generally show that the chlorite-rich rims formed first, followed by infilling with quartz. Calcite occurs as the latest mineral phase within the ovoids.

Locally, zones enriched in pyrite occur in the Canagau Mine area and the Croxall Property. These zones contain disseminated pyrite and minor amounts of other sulphides and occur within the larger alteration zones surrounding both mineral occurrences. A zoning of sulphide abundance is more pronounced at the Croxall Property where the mineralization is in the form of a breccia-pipe from which sulphur-rich fluids circulated outward into the surrounding host rock. The effects of S enrichment will be shown in the subsequent treatment of the data.

LITHOGEOCHEMISTRY

The samples used in this study were collected from three sources. These are:

1. samples collected by Jensen (1975)
2. samples collected by Wolfe (1977)
3. samples collected by the author from 1979 to 1981

The samples collected by Jensen and Wolfe were analyzed by techniques outlined by Wolfe (1977, p.10); samples collected by the author were analyzed by methods outlined by Grunsky (in preparation). A total of 864 samples were used for the study and 39 components were analyzed for each sample: SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MgO , CaO , Na_2O , K_2O , TiO_2 , P_2O_5 , MnO , CO_2 , S, H_2O^+ , H_2O^- , Ag, As, Au, Ba, Be, Bi, Cl, Co, Cr, Cu, F, Ga, Li, Ni, Pb, Zn, B, Mo, Sr, V, Y, Zr, Sc, and Sn. Every outcrop sampled in the area is represented in the data by at least one sample typical of the outcrop. Figure 8.4 shows the distribution of the samples over the area. It is important to note that the distinction between pervasive and non-pervasive alteration cannot be distinguished by lithogeochemistry alone.

Complications in sampling commonly occurred because many breccia units are heterolithic and because amygdaloidal rocks are highly variable in amygdule/ovoid content. One of the purposes of the study was to determine if any significant indications of alteration could be detected by sampling the typical or dominant rock type of a given outcrop. Thus, samples were selected for their geochemical signature with respect to alteration as opposed to their original rock type. The lithogeochemistry of a carbonatized heterolithic breccia may not provide a useful indication of the different rock types that comprise the unit; however, the amount of CO_2 present will show up regardless of the rock types involved. On the other hand, the lithogeochemistry of a silicified heterolithic breccia will probably not reflect an increase in silica since the rock might be interpreted as a rhyolite. Such problems had to be considered in the interpretation of lithogeochemical data.

Samples rich in sulphides were collected and analyzed; however, some were eliminated in the subsequent data processing. Such samples tend to exhibit highly varied component abundances. This causes spiked peaks in spatially distributed anomalies and can mask the more subtle lithogeochemical indicators of alteration. Because sulphide-rich rocks are very different compositionally from unmineralized volcanic rocks, they tend to produce a high degree of variance in the data and can result in misleading interpretations. Emphasis in this study has been placed on selecting samples that will yield broad generalized patterns of alteration detectable on a reconnaissance scale that enable selection of sites for mineral exploration.

ISO-CHEMICAL CONTOUR PLOTS

Figures 8.5 through 8.21 contain isochemical contour plots of the elements that were analyzed for the study. The contour diagrams are modified from plots drawn by the Surface II Graphics Systems (Sampson 1975). Each figure is composed of two parts. Figure "A" shows the contoured raw data. Figure "B" shows the "residual" value of the chemical component, that is, the abundance of a chemical component after an "expected" value has been subtracted from the actual abundance. The "expected" value is defined as the component abundance that would be expected for a given rock type.

These expected values were defined in the following way. The standards (expected values) were computed from the lithogeochemical database for the study area only. This was done because rock types that are "normal" (unaltered) in the Ben Nevis area may be somewhat different in composition from other areas.

Each sample was classified using the chemical classification methods of Irvine and Baragar (1971) and Jensen (1976). For each chemically classified group of samples (for example, calc-alkalic basalts), a mean and standard deviation was computed for each chemical component. Every component of each sample was then compared with the mean of each component for the calculated group. If the component value exceeded the mean plus two standard deviations, then the sample was rejected. A new mean for each component of each group was calculated on the sample population that was not rejected, and the comparison of the samples with the new mean values was repeated. This method was carried out three times, forcing a "normal" or "expected" value on each chemical component of each chemically classified group.

This can be thought of as a method of correcting or normalizing the geochemical data which is required because of the natural chemical variation in a volcanic suite even before alteration. This method has limitations and is discussed below.

The unprocessed (Figure "A") isochemical plots typically reflect three phenomena:

1. compositional variation due to rock type
2. regional zones of alteration (regional carbonatization, Ca depletion)

3. local zones of mineralization-chalcophile distribution

Typically, the spatially mapped abundances of SiO_2 (Figure 8.5a), Al_2O_3 (Figure 8.6a), Fe_2O_3 (Figure 8.7a), FeO (Figure 8.8a), MgO (Figure 8.9a), CaO (Figure 8.10a), K_2O (Figure 8.12a), TiO_2 (Figure 8.13a), CO_2 (Figure 8.14a), H_2O^+ (Figure 8.16a), and Ni (Figure 8.20a) reflect the compositional variation. However, some elements such as MgO , CaO , Fe_2O_3 , Zn , Cr , and H_2O not only vary with composition due to rock type, but also vary in abundance due to the effects of hydrothermal alteration. Elements such as Au (Figure 8.17a), Cu (Figure 8.18a), Zn (Figure 8.21a), Pb , and Sn are typically low in abundance at the regional scale. Locally, high abundances of these components are often found around zones of alteration and/or mineralization. Zinc is unique because it can substitute for Fe^{+2} in lattices of ferromagnesian minerals; thus, its abundance varies directly with rock composition. Hydrothermal alteration can cause the breakdown of these ferromagnesian minerals. This frees the Zn. In the vicinity of an alteration halo, the Zn may recombine in part with S, and substitute into the chlorite lattice to create an anomaly associated with rock composition, hydrothermal alteration, and sulphide concentration.

The association of certain components with alteration and mineralization cannot always be easily detected. As discussed earlier, compositional variation due to rock type can mask these secondary features. If the influence due to rock type is removed, it is possible to "see" which components have been affected by alteration, and which are associated with mineralization. To "normalize" or correct for rock type, the expected value of the component is subtracted from its measured value, the difference being termed the "residual". The "residual" value does not necessarily reflect the amount of alteration. Some components such as SiO_2 show a highly variable concentration in individual rock types. Residual values should only be considered anomalous if greater than the standard deviation or some other determined confidence level. Figure 8.5b shows SiO_2 anomalies with residual values $>4.0\%$ (silicification) and $<4.0\%$ (silica leaching). The pattern is erratic over the area, but locally, strong silica enrichment is seen in the vicinity of the Canagau Mine Deposit and the Croxall Property. Silica depletion occurs in sulphide-rich zones and mafic plutons.

More typically, residuals reflect the components associated with alteration and mineralization. Components such as Al_2O_3 (Figure 8.6b), Fe_2O_3 (Figure 8.7b), MgO (Figure 8.9b), CaO (Figure 8.10b), K_2O (Figure 8.12b), TiO_2 (Figure 8.13b), CO_2 (Figure 8.14b), Li (Figure 8.19b), Ni (Figure 8.20b), and Zn (Figure 8.21b) show anomalous abundances in the form of addition or depletion around the Canagau Mines Deposit and the Croxall Property. Elements that are typically considered to be "immobile" under most conditions, such as Al_2O_3 (Figure 8.6b), TiO_2 (Figure 8.13b), Ni (Figure 8.25b) have in fact undergone considerable changes in abundance.

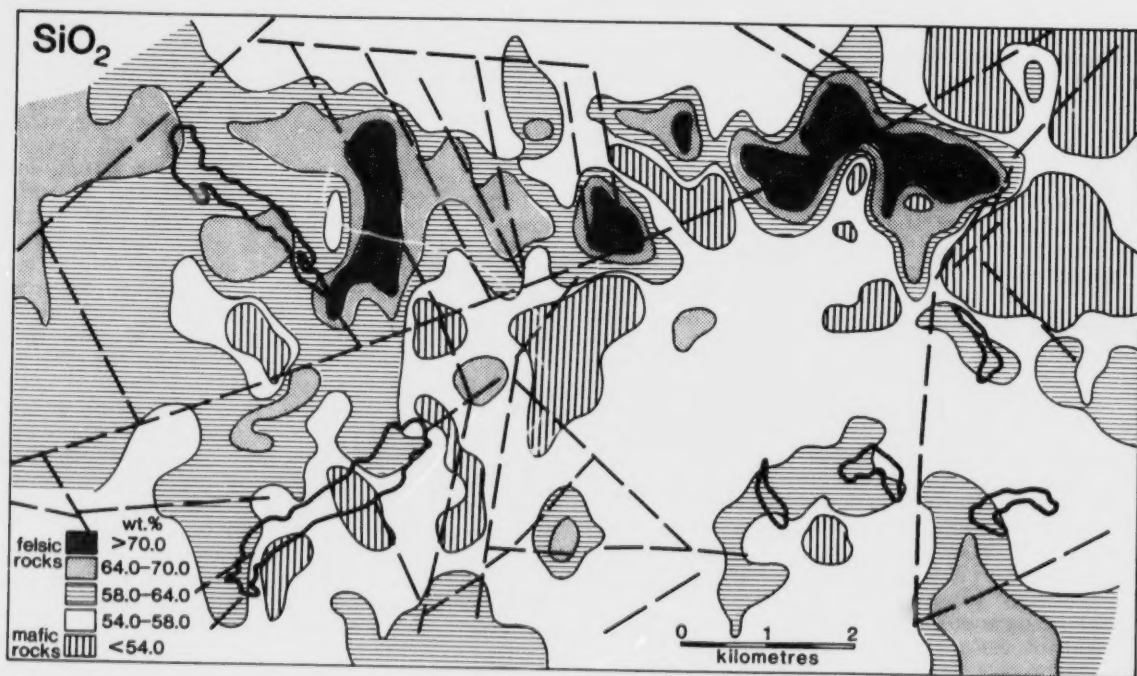


Figure 8.5a. Distribution of SiO_2 outlining rock types.

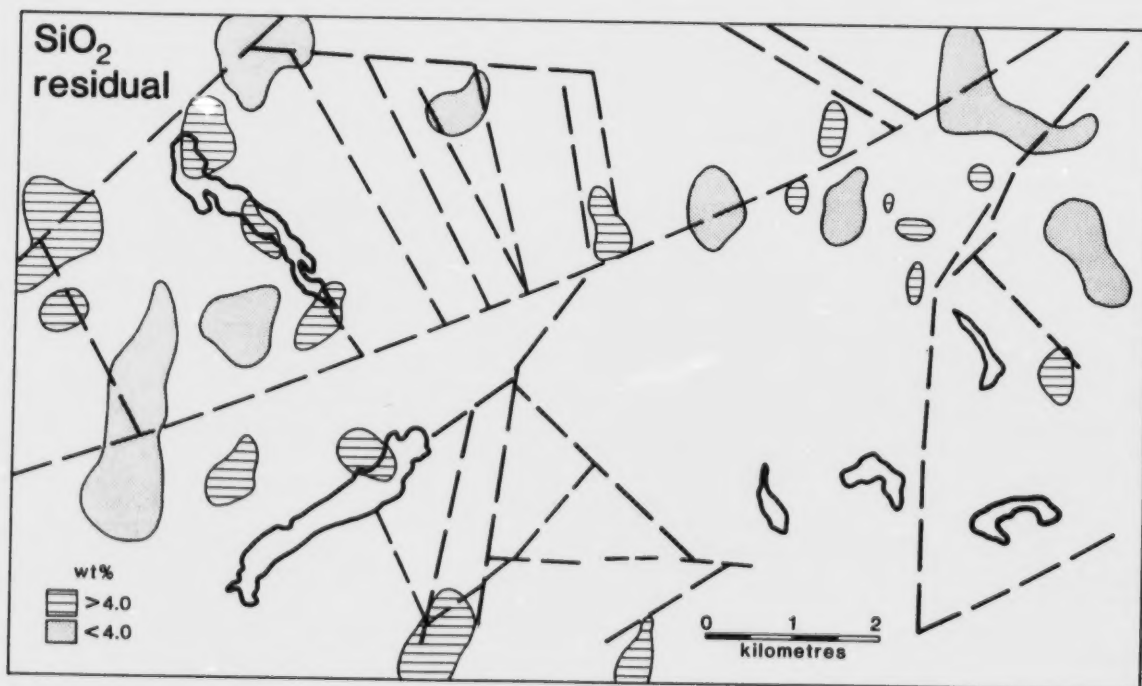


Figure 8.5b. SiO_2 residual, showing small zones of addition/depletion due to alteration and misclassification (plutonic rocks).

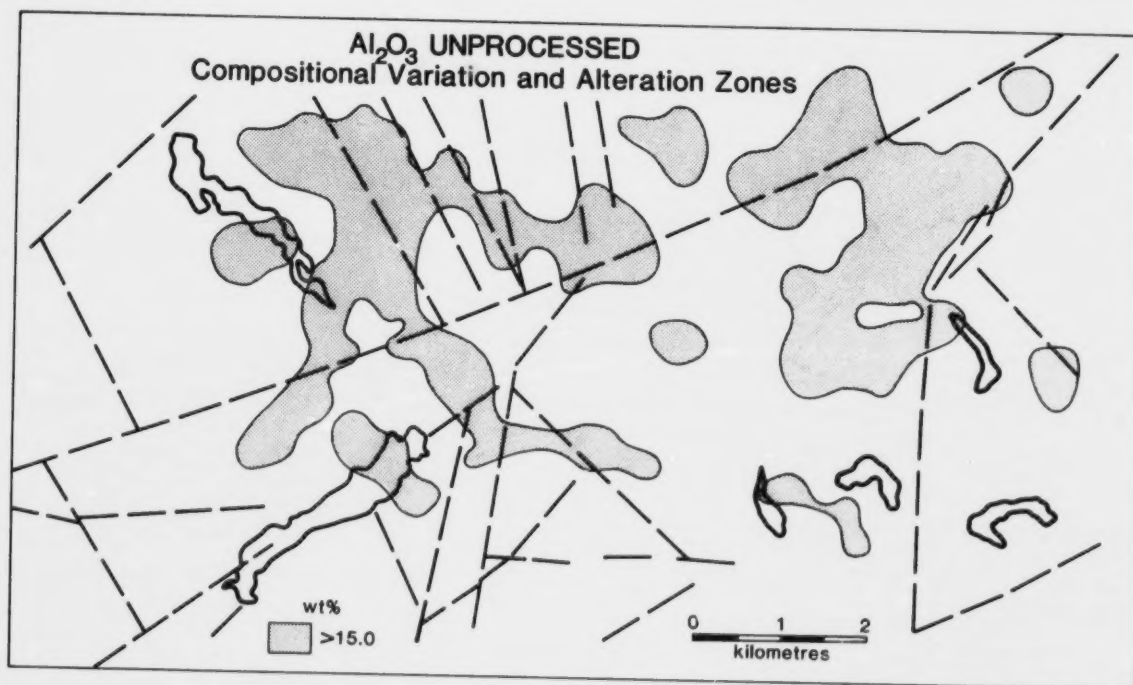


Figure 8.6a. Al₂O₃ unprocessed, showing compositional variation and alteration zones.

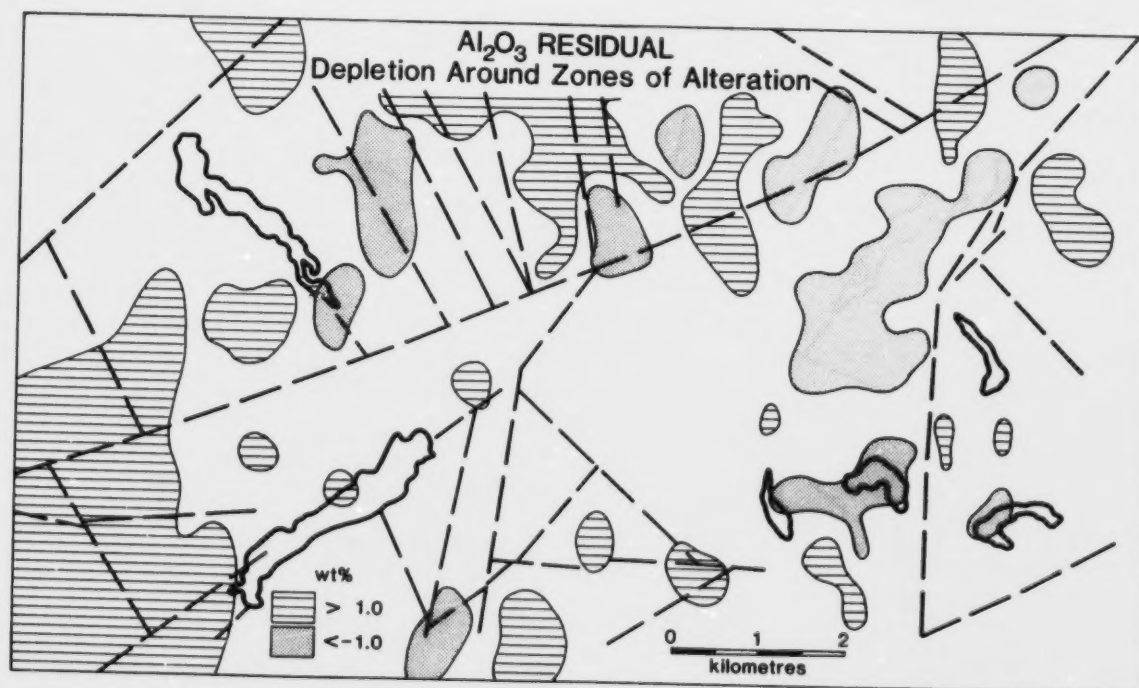


Figure 8.6b. Al₂O₃ residual, showing depletion around zones of alteration.

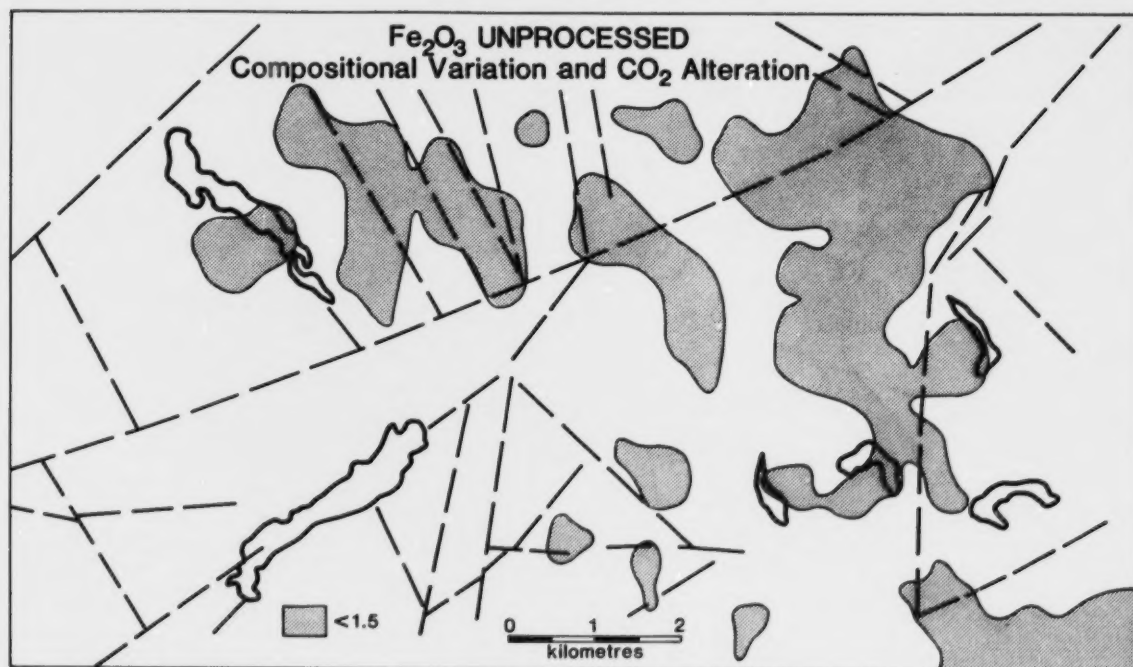


Figure 8.7a. Fe₂O₃ unprocessed, showing compositional variation and CO₂ alteration.

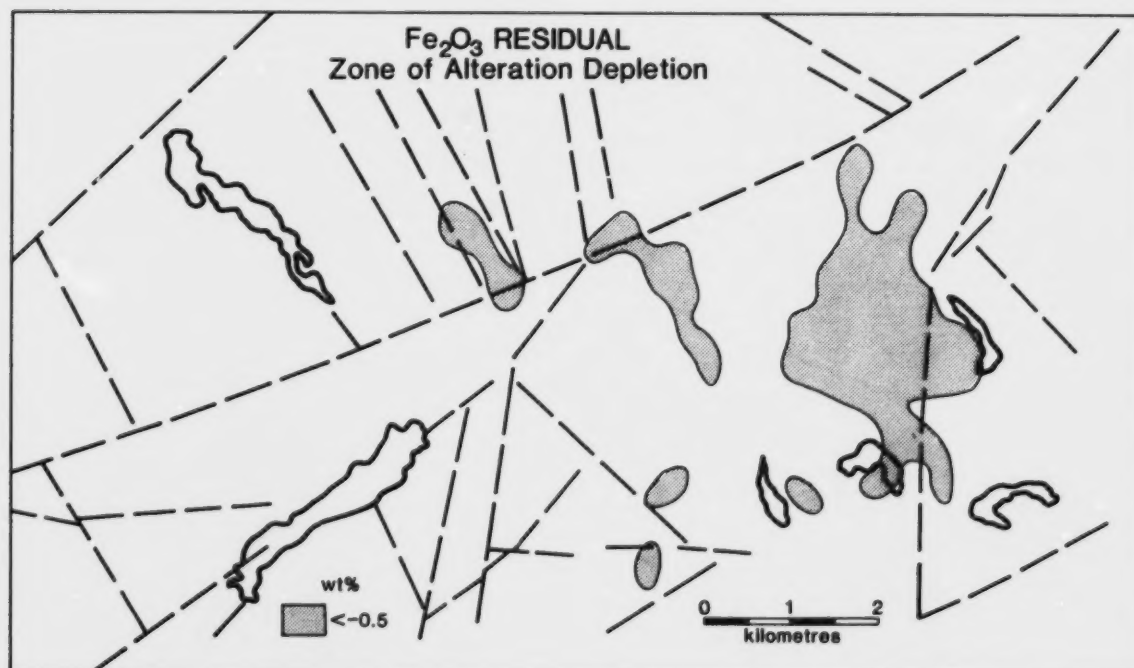


Figure 8.7b. Fe₂O₃ residual, showing zone of alteration and depletion.

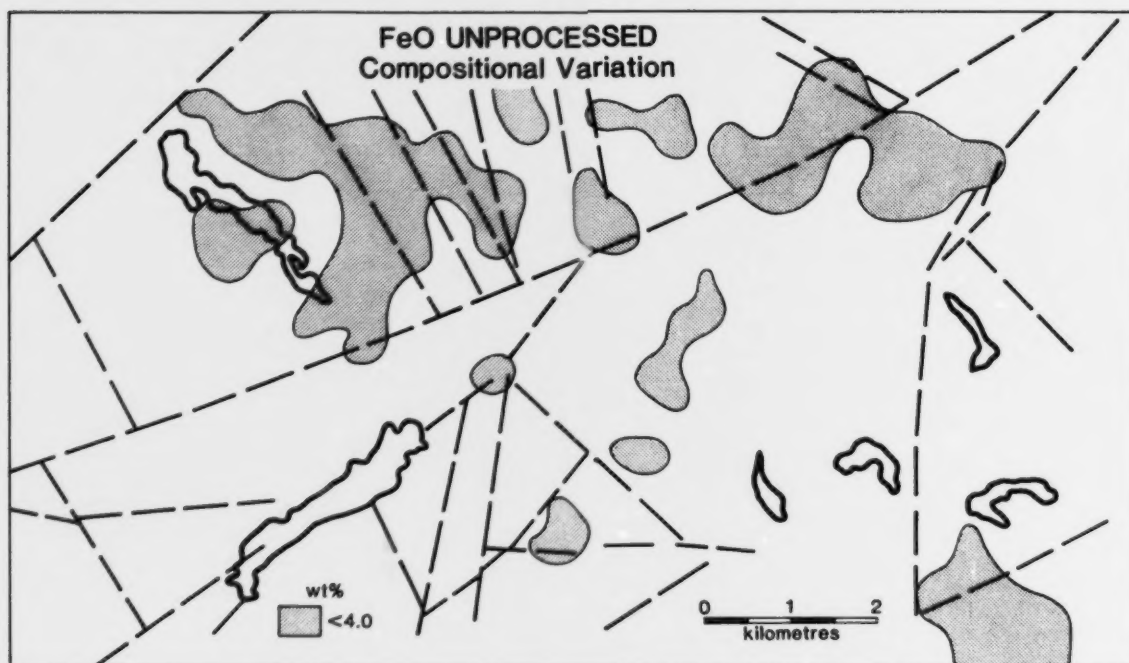


Figure 8.8a. FeO unprocessed, showing compositional variation.

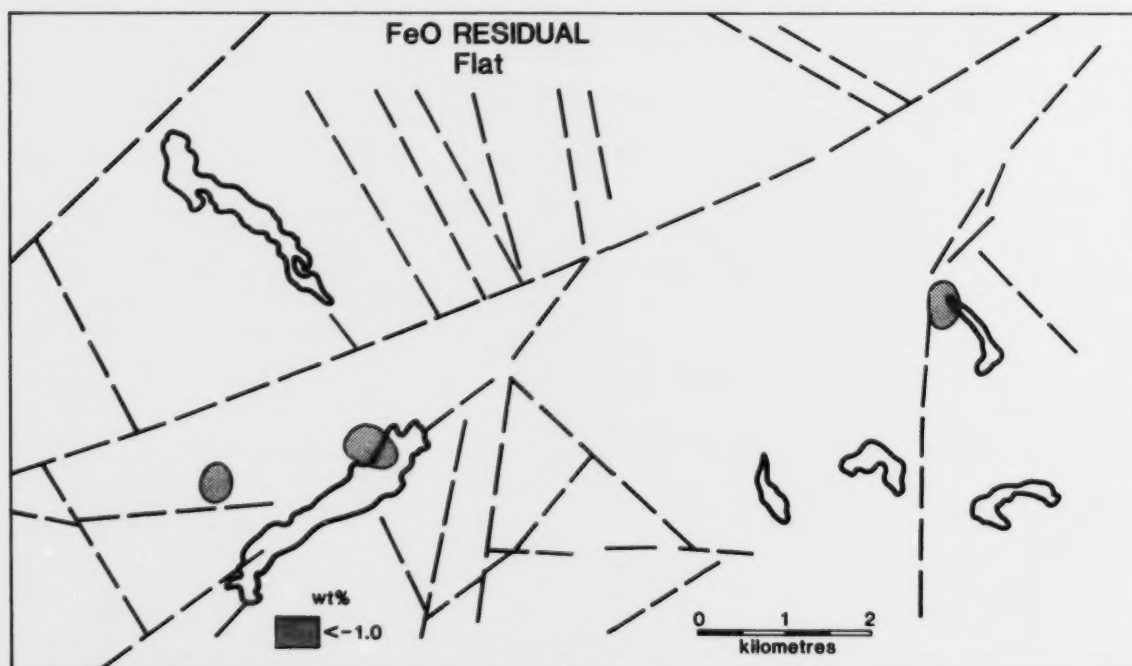


Figure 8.8b. FeO residual, showing minor depletion around Canagau Mine, Croxall Property, and Verna Lake Stock.

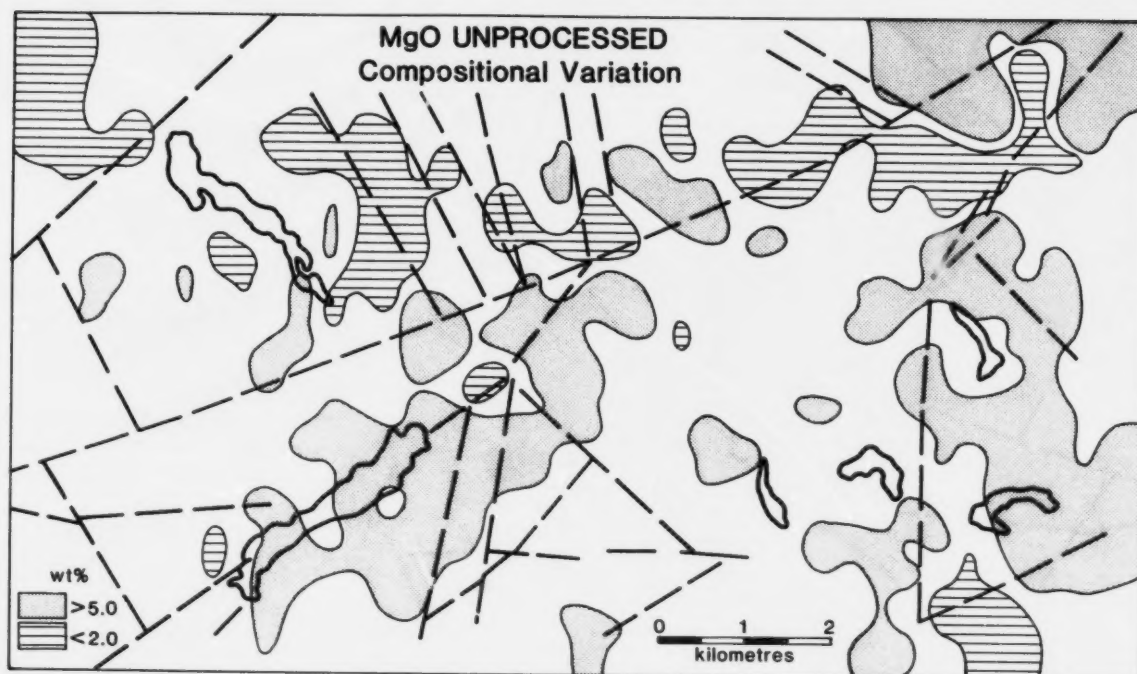


Figure 8.9a. MgO unprocessed, showing compositional variation.

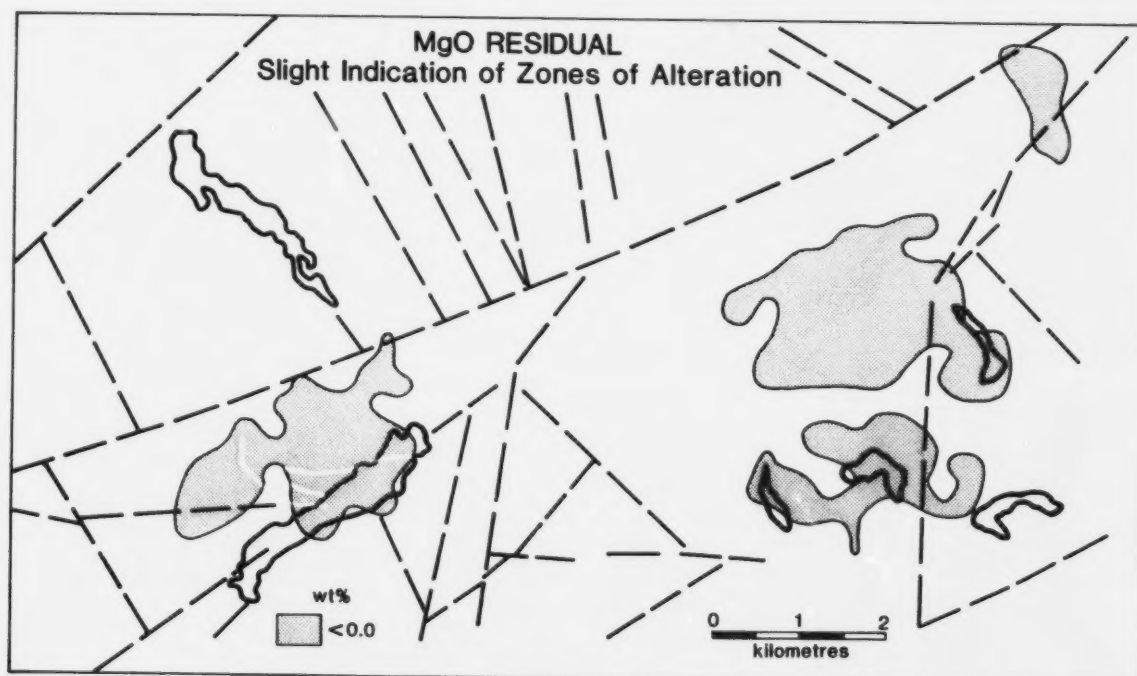


Figure 8.9b. MgO residual, showing slight indication of alteration zones.

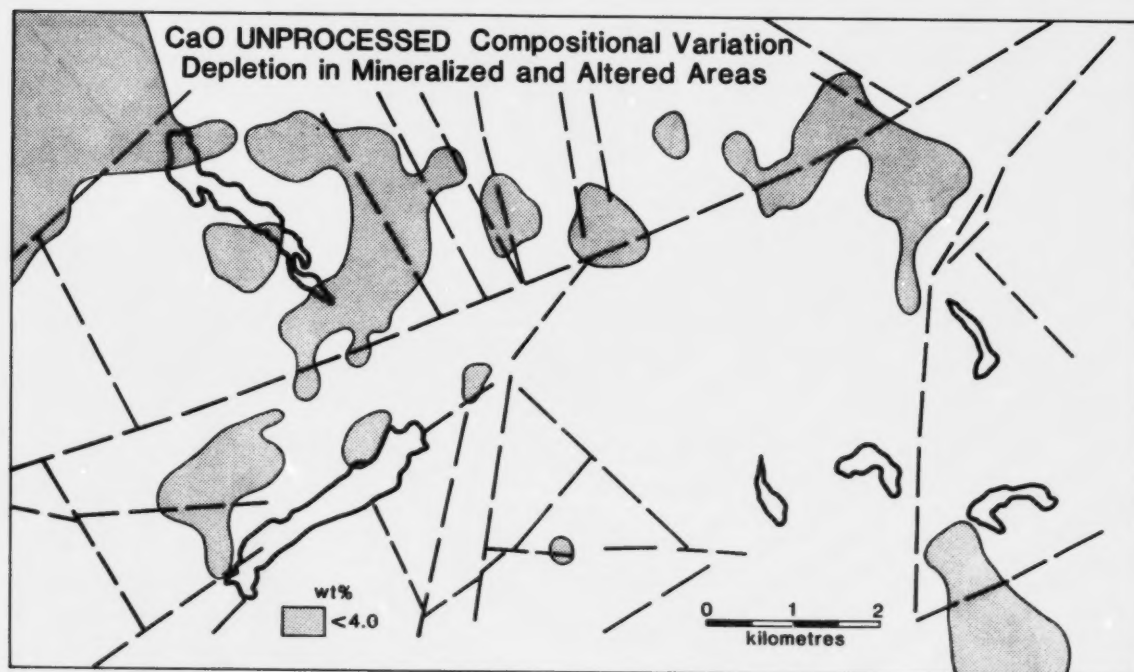


Figure 8.10a. CaO unprocessed, showing compositional variation and depletion in mineralized and altered areas.

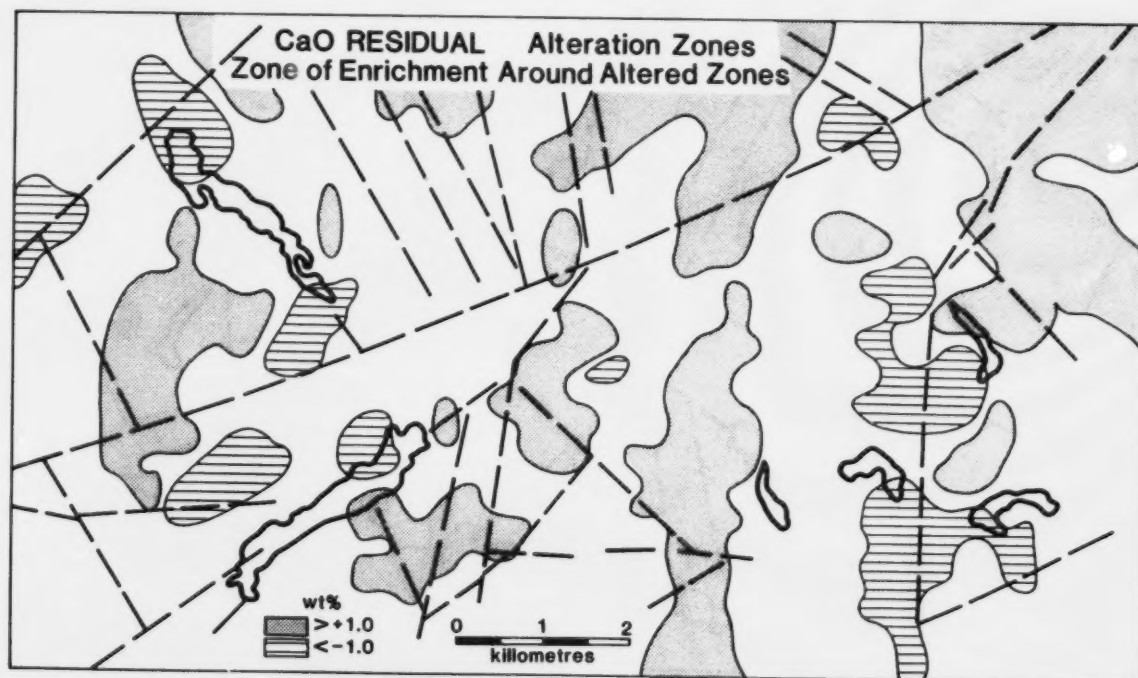


Figure 8.10b. CaO residual, showing depletion around alteration zones and zone of enrichment around altered zones.

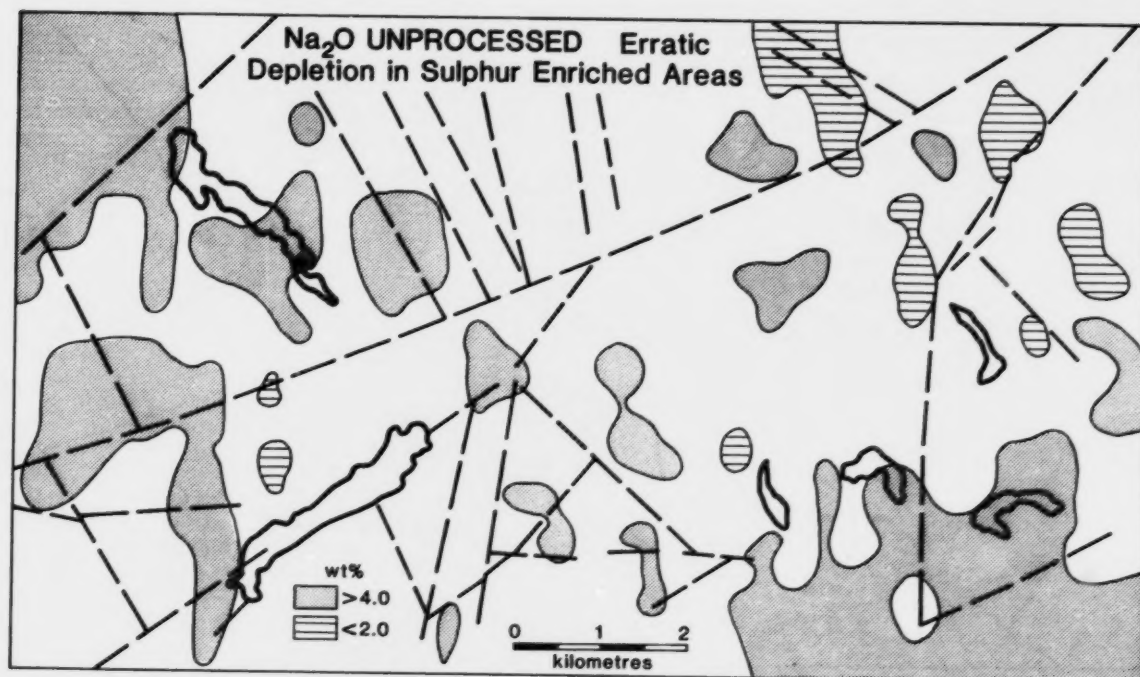


Figure 8.11a. Na₂O unprocessed, showing erratic depletion in S enriched areas.

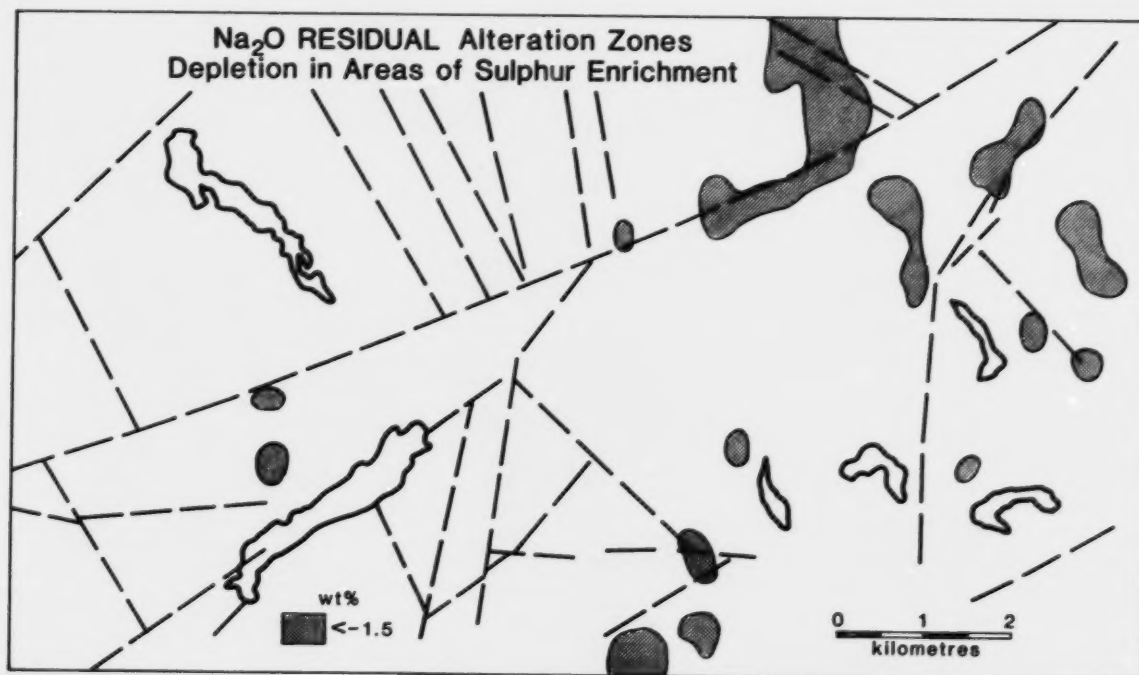


Figure 8.11b. Na₂O residual, showing alteration zones and depletion in areas of S enrichment.

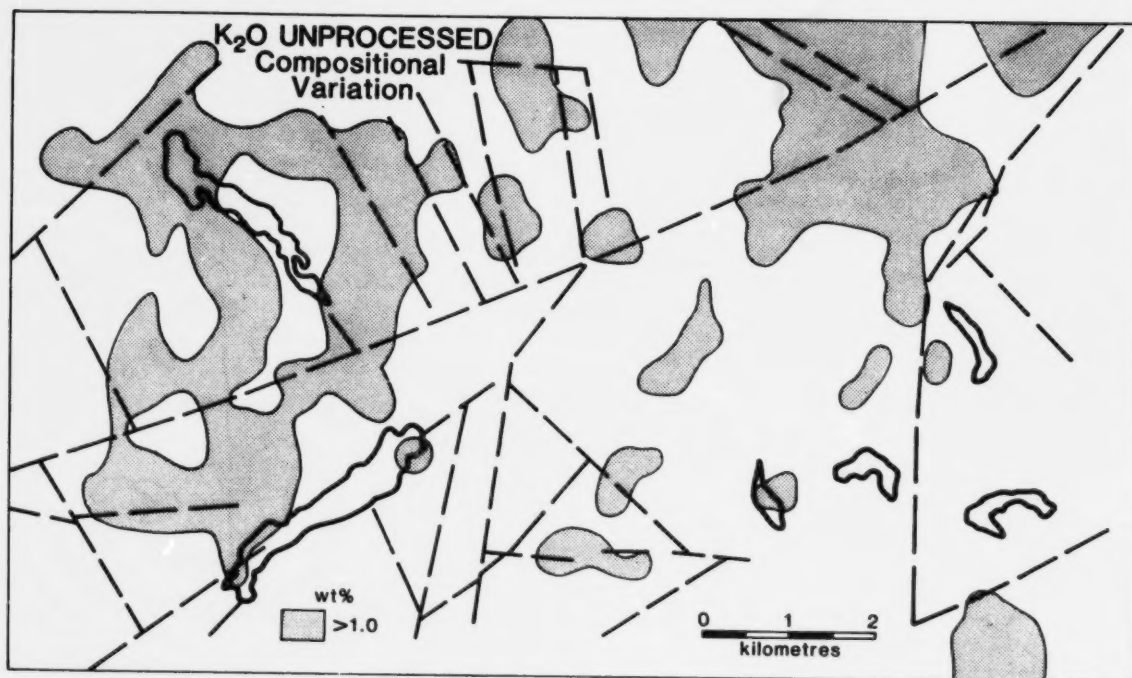


Figure 8.12a. K_2O unprocessed, showing compositional variation.

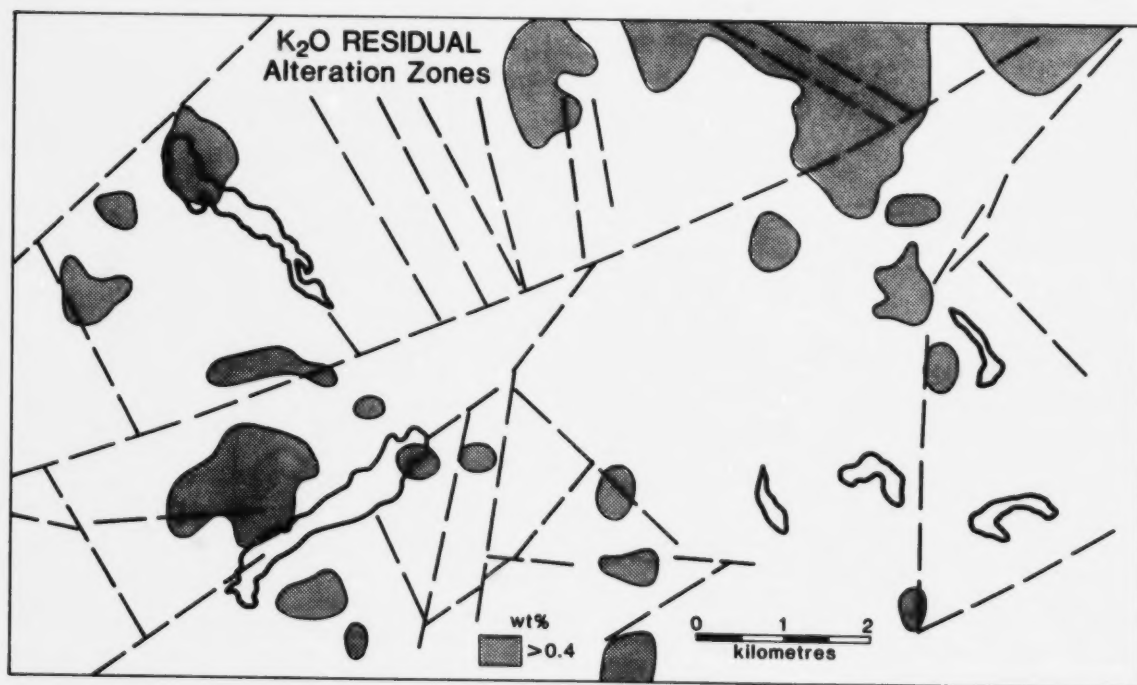


Figure 8.12b. K_2O residual, showing enrichment in alteration zones.

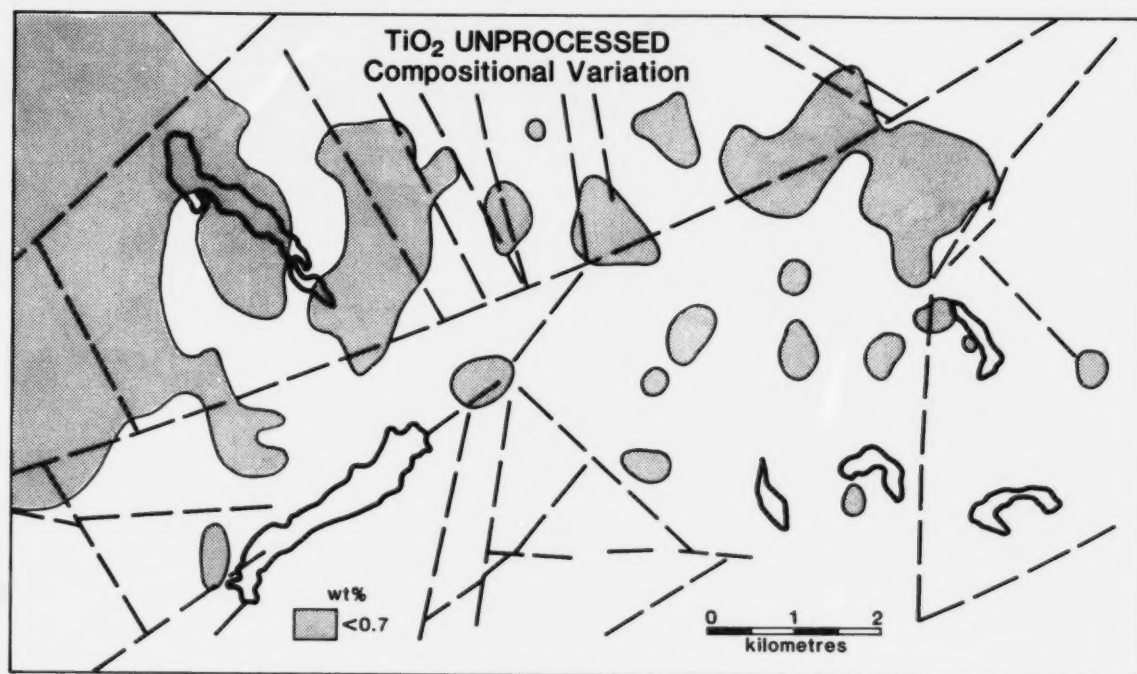


Figure 8.13a. TiO_2 unprocessed, showing compositional variation.

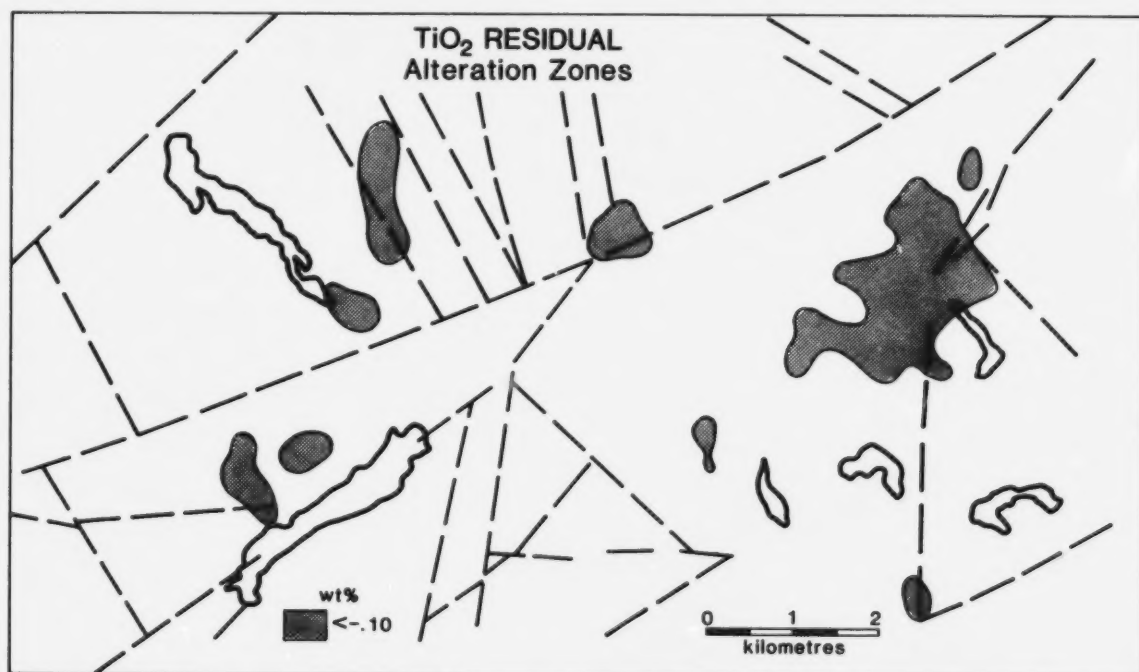


Figure 8.13b. TiO_2 residual, showing depletion in alteration zones.

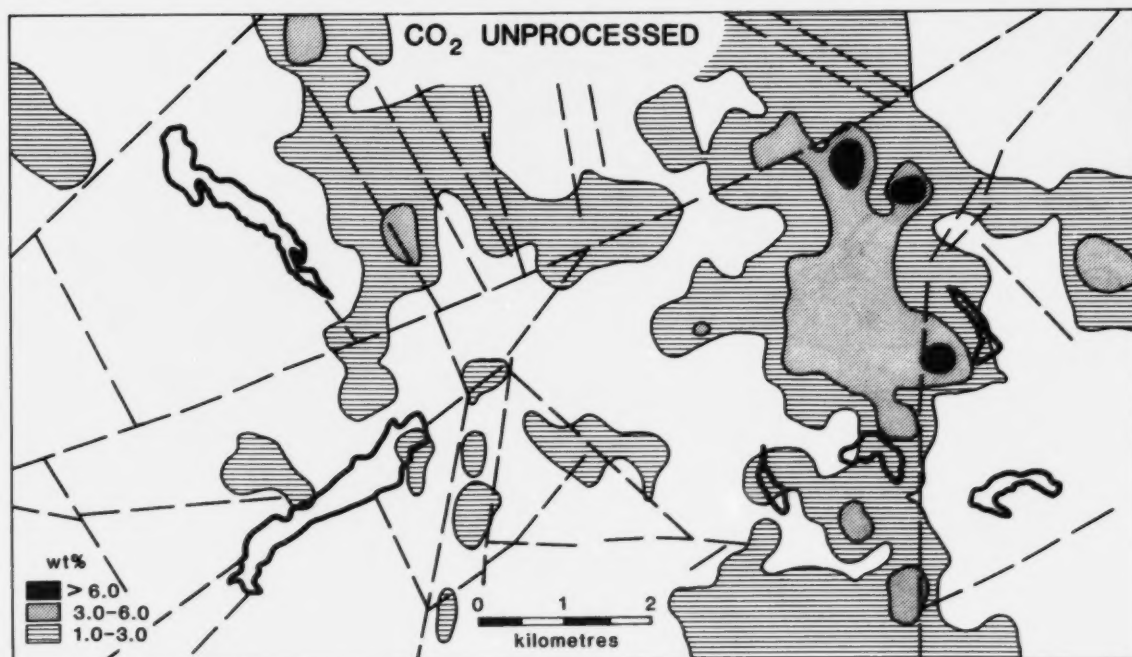


Figure 8.14a. CO₂ unprocessed, showing hydrothermal alteration.

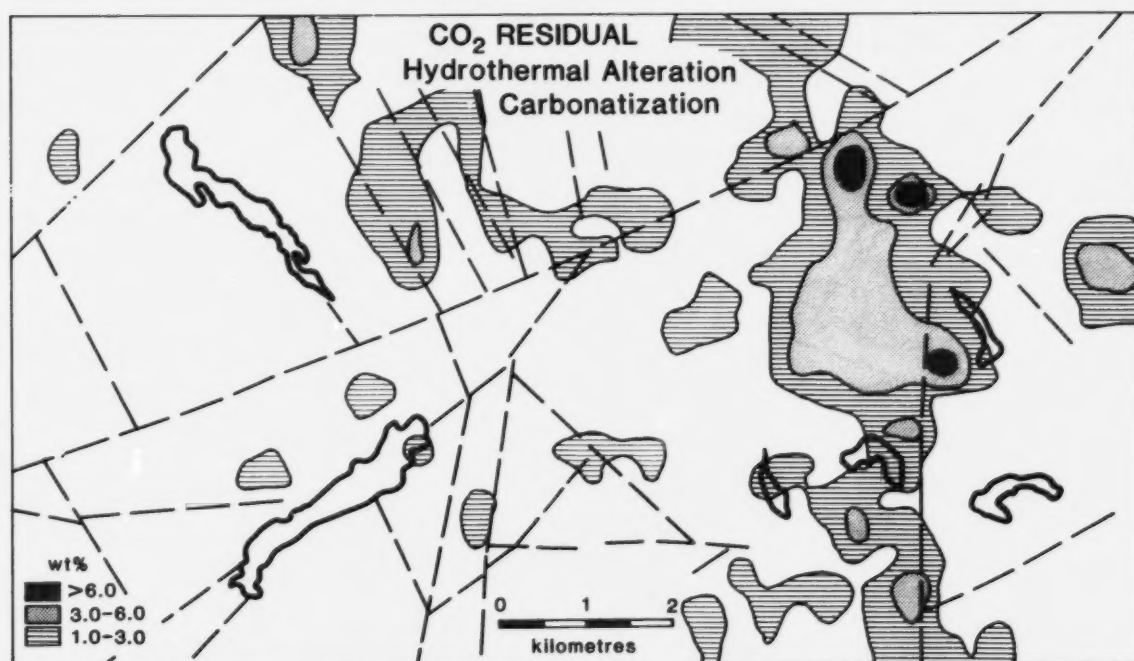


Figure 8.14b. CO₂ residual, showing hydrothermal alteration and carbonatization.

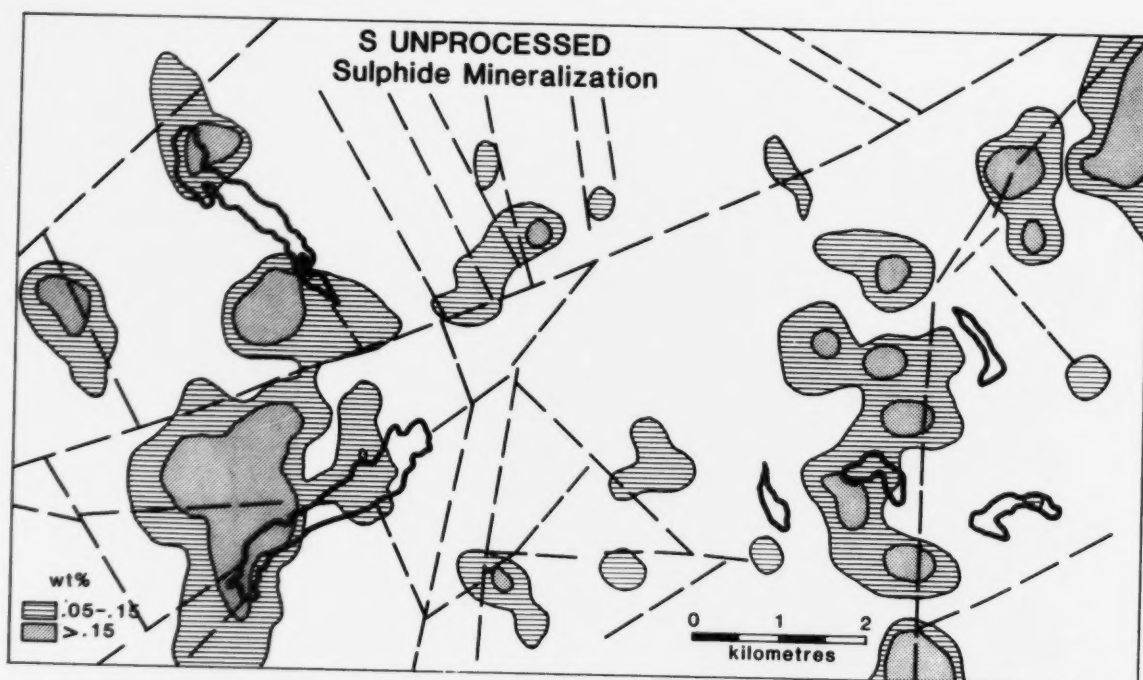


Figure 8.15a. Sulphur unprocessed, showing sulphide mineralization.

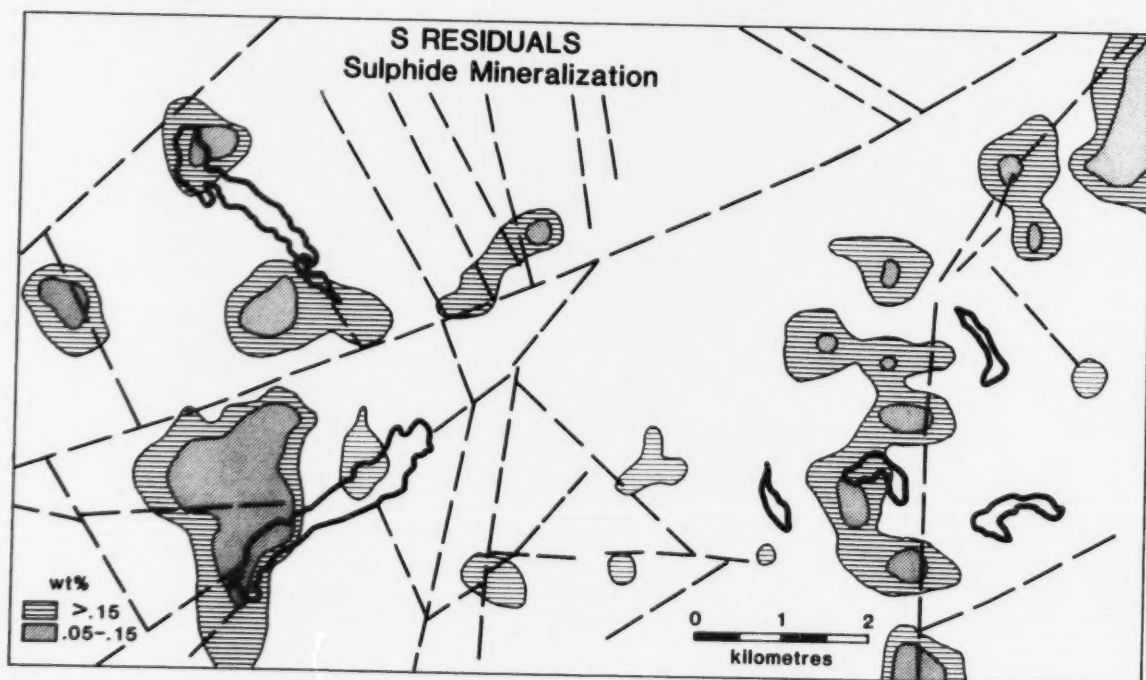


Figure 8.15b. Sulphur residuals, showing sulphide mineralization.

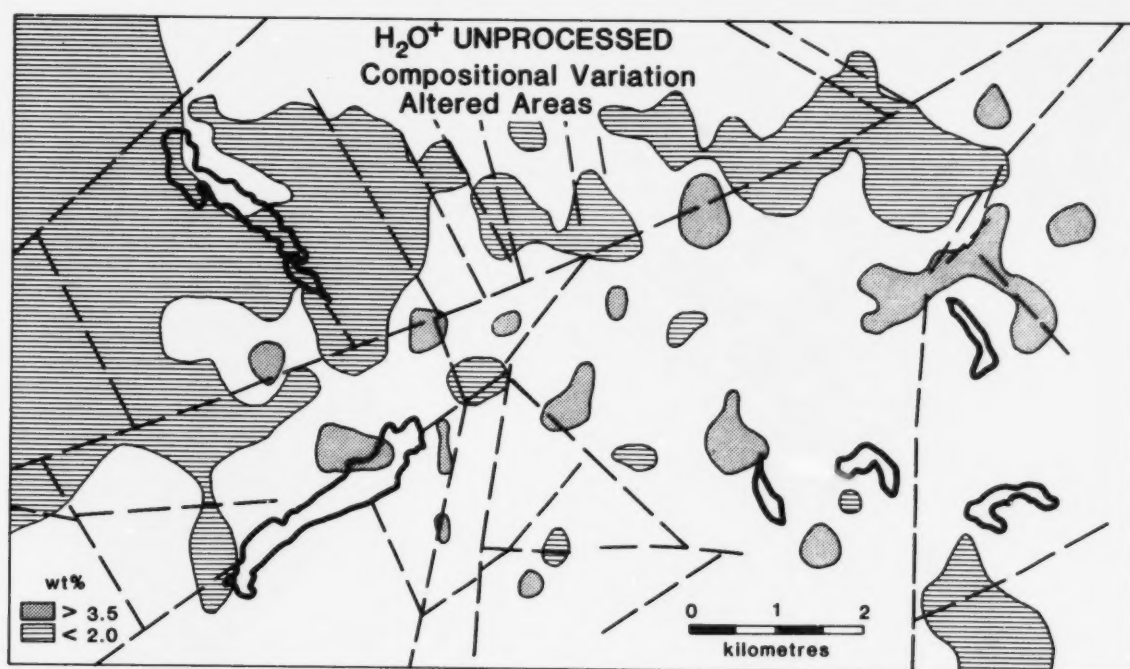


Figure 8.16a. H₂O⁺ unprocessed, showing compositional variation and some indication of alteration zones.

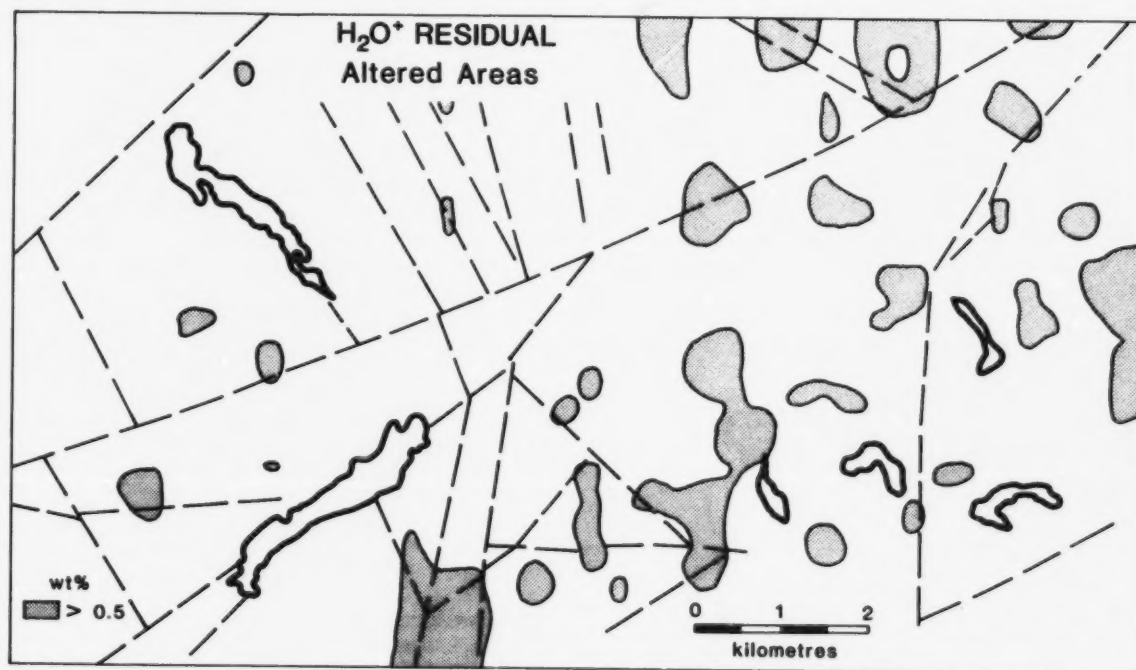


Figure 8.16b. H₂O⁺ residual, showing slight indication of alteration zones.

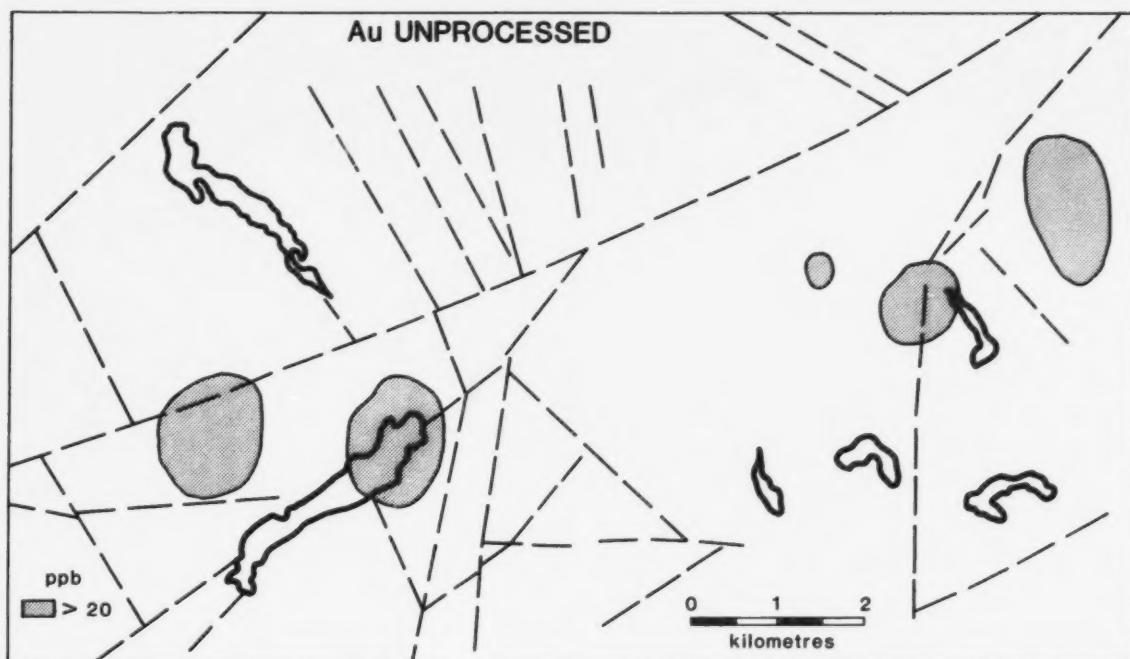


Figure 8.17a. Gold unprocessed, showing enrichment.

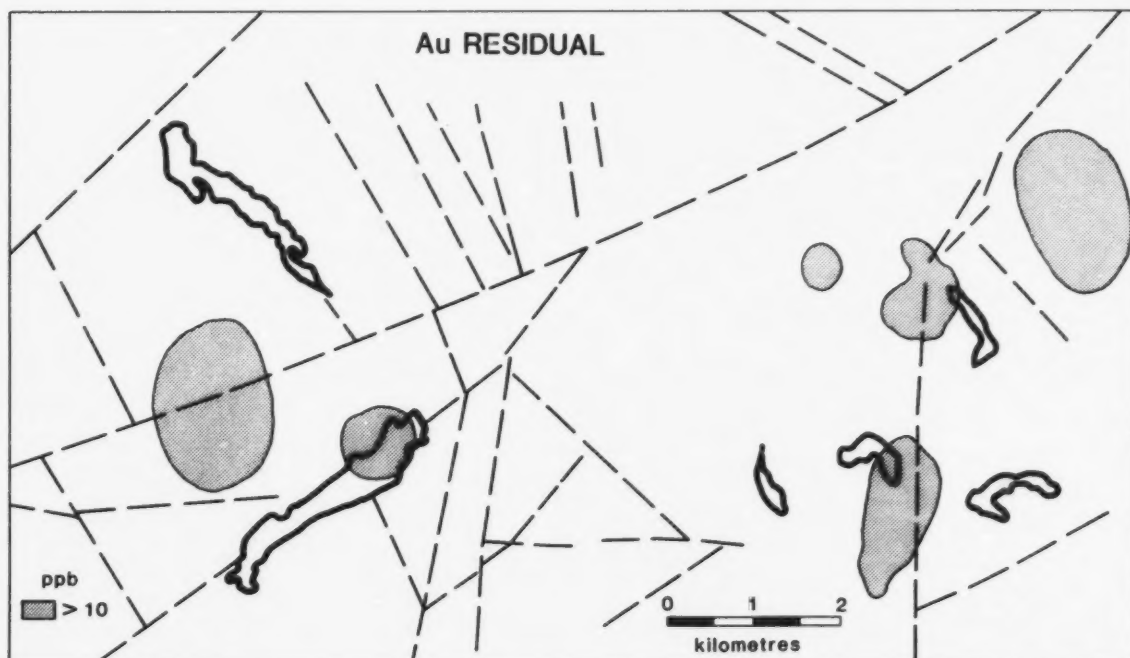


Figure 8.17b. Gold residual, showing enrichment.

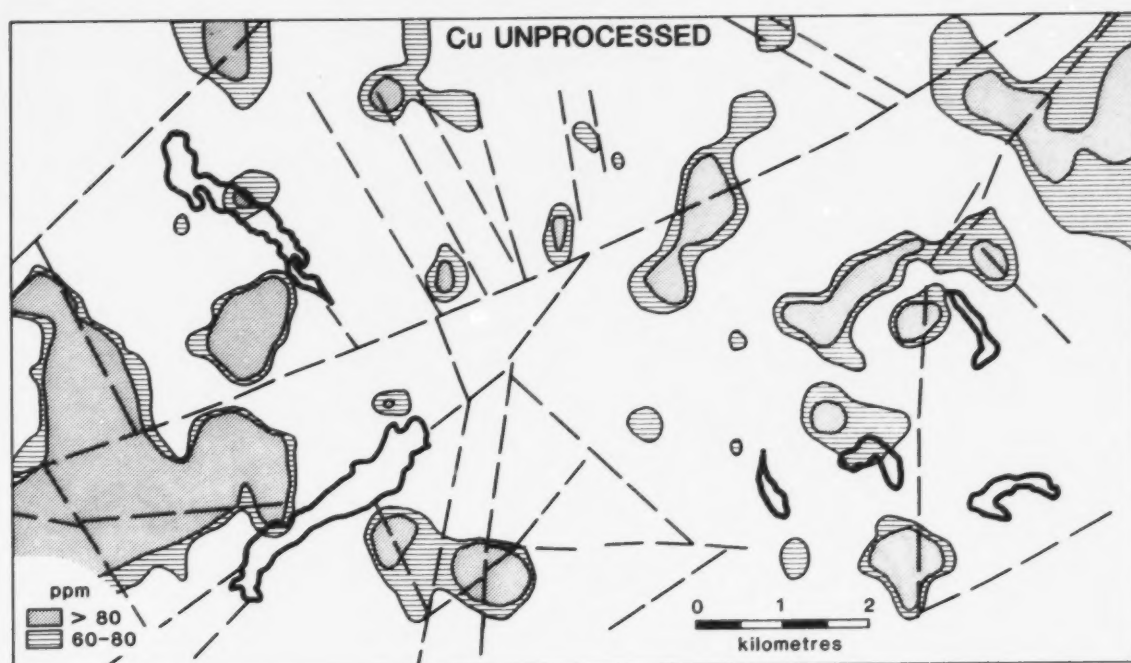


Figure 8.18a. Copper unprocessed, showing local enrichment.

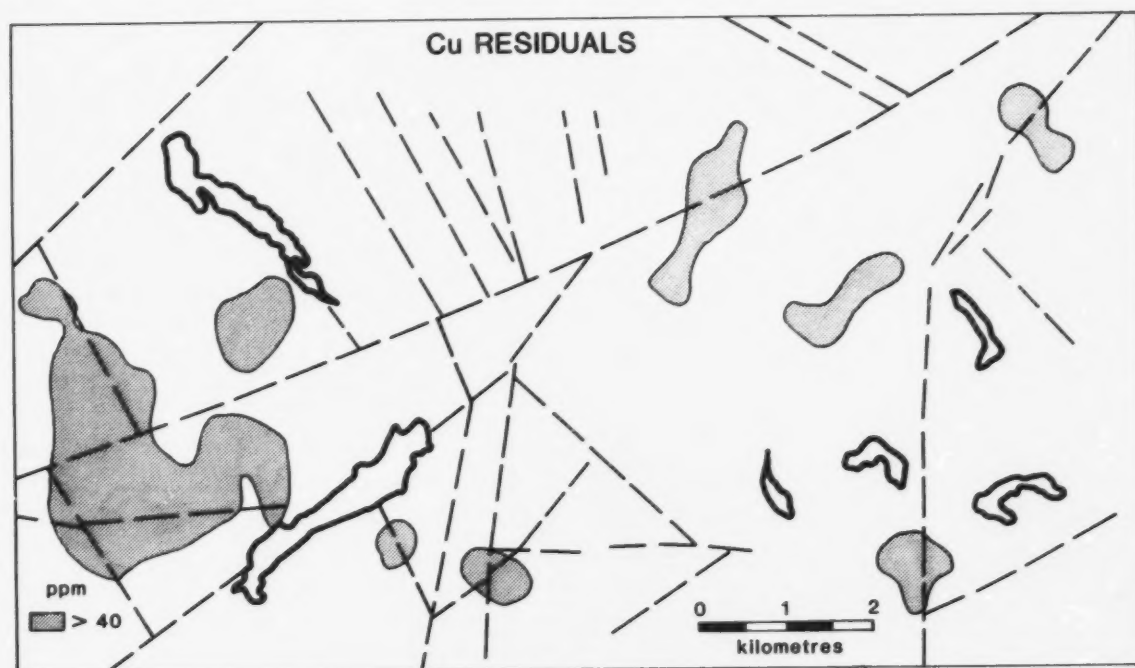


Figure 8.18b. Copper residuals, showing enrichment.

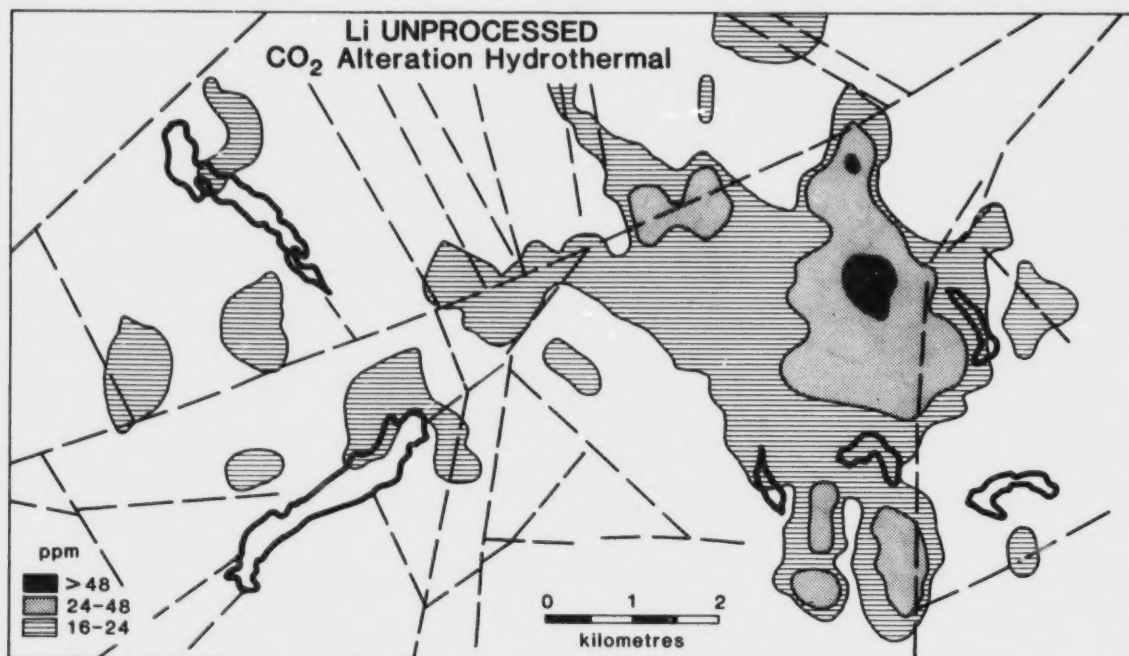


Figure 8.19a. Lithium unprocessed, showing hydrothermal alteration.

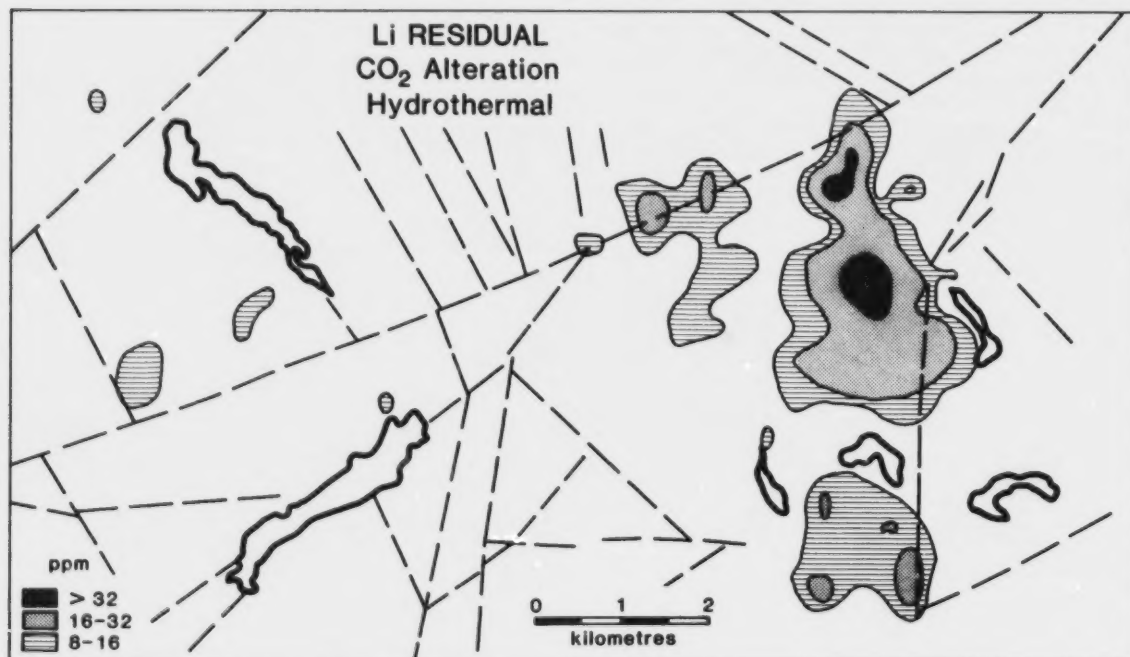


Figure 8.19b. Lithium residual, showing CO₂ alteration hydrothermal.

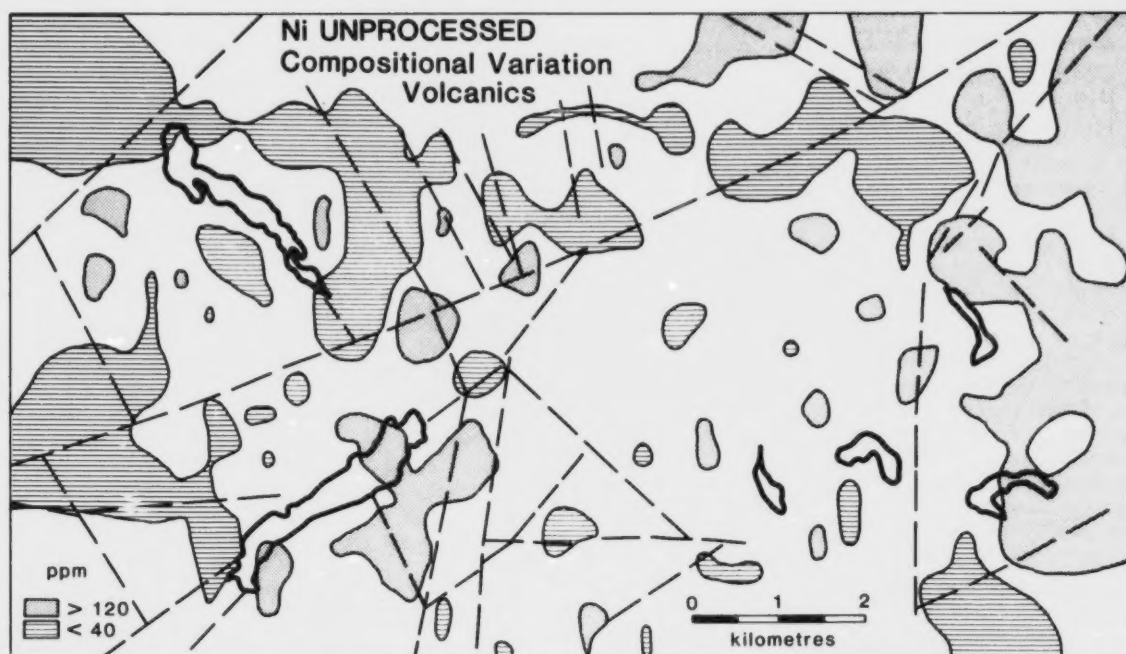


Figure 8.20a. Nickel unprocessed, showing compositional variation in volcanic rocks.

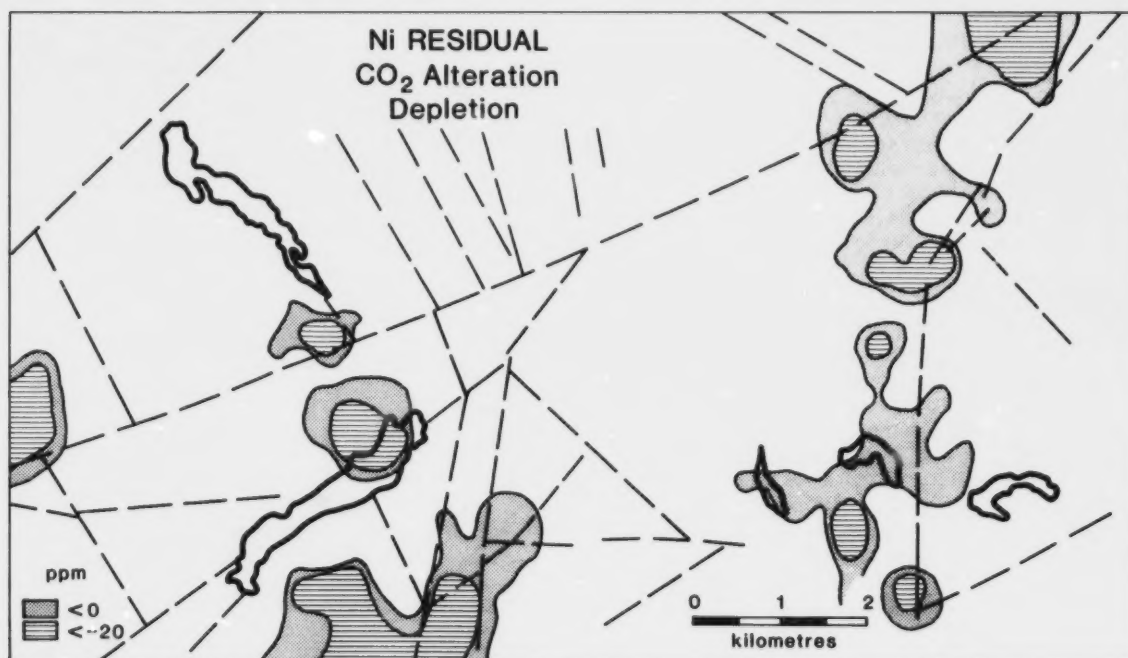


Figure 8.20b. Nickel residual, showing alteration zones.

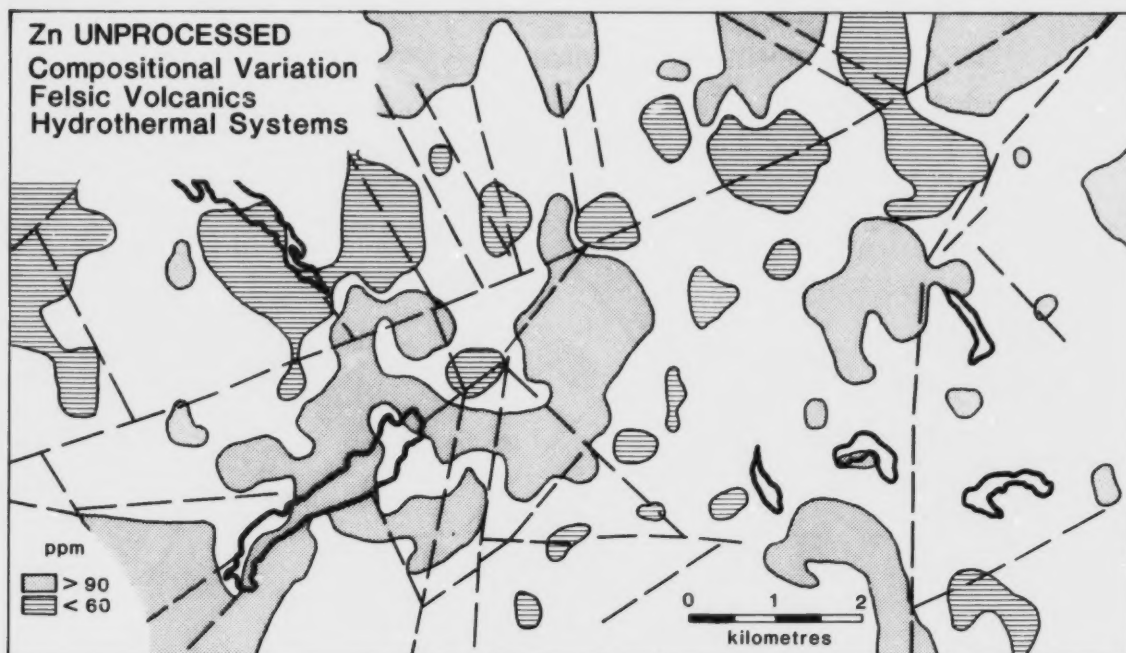


Figure 8.21a. Zinc unprocessed, showing compositional variation of volcanic rocks and hydrothermal alteration.

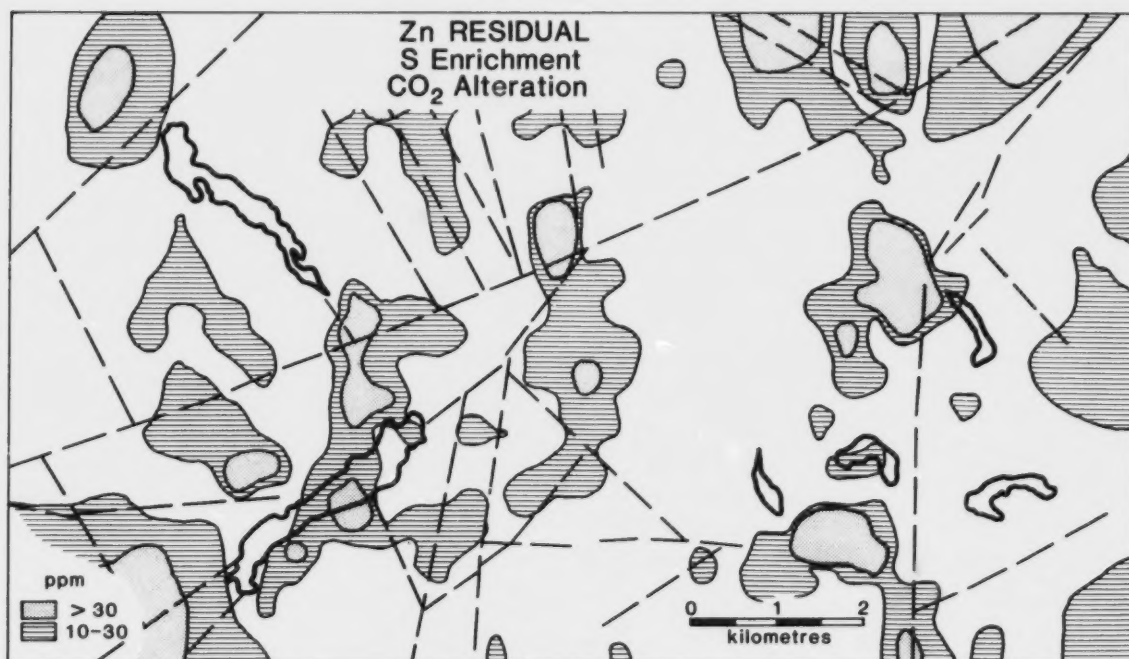


Figure 8.21b. Zinc residual, showing sulphur enrichment and CO₂ alteration.

NORMALIZATION SCHEMES AND TECHNIQUES FOR IDENTIFYING ALTERATION

Sopuck (1977), Sopuck *et al.* (1980), and Lavin (1976) used SiO_2 as an independent variable against which all other oxide/element abundances would be measured. Regression curves were derived for each oxide/element with respect to SiO_2 . Residuals were then computed based on the actual abundance of an oxide/element in comparison to its expected value determined from the SiO_2 content of the rock and the regression formula. This classification scheme works providing the original SiO_2 content of the volcanic rocks has not changed. Studies by Gibson *et al.* (1983), Franklin and Thorpe (1982), Deptuck *et al.* (1982), Knuckey *et al.* (1982), Urabe and Sato (1978), Knuckey and Watkins (1982), Riverin and Hodgson (1980), and MacGeehan and MacLean (1980) all show that SiO_2 as well as other oxides/elements are mobile in altered volcanic domains. Thus, the use of any individual oxide/element as an independent or "immobile" variable by which the expected abundance of other components can be determined is questionable.

In this study, the two classification schemes which are used are based on components that are known to be mobile. The classification scheme of Jensen (1976) uses Al, Fe^3 , Fe^2 , Ti, Mn, and Mg; but Mg and Fe are known to be mobile around sulphide deposits (Riverin and Hodgson 1980; Knuckey *et al.* 1982). The classification scheme of Irvine and Baragar (1971) uses Na_2O , K_2O , MgO , FeO , SiO_2 , and Al_2O_3 . Na and K are particularly mobile in altered areas and in regional metamorphic domains. This can cause significant errors in the classification of the volcanic rocks. All classification schemes will fail when the independent variables used are susceptible to alteration. The mobility of these components can be readily recognized because their use will lead to inconsistent results within the classification scheme. If a rock is misclassified because the critical components to make a particular classification have been altered, the expected values for other components within that sample are likely to show abnormal abundances. As an example, if a basalt has been silicified, a regression equation would indicate that the Na or K are too low and Ti, Fe, and Mg are too high. These would show up as large residual values on contour maps. Similarly, the use of the cation classification scheme of Jensen (1976), should show that rocks enriched in Mg will indicate high residual values in Si and Al.

Various classifications exist in which the calculation of residual values is part of the classification process. They can be used successfully if properly interpreted. However, the problems stated above are unavoidable, and interpretation of residual data must take these problems into account.

Beswick and Soucie (1978) and Beswick (1981) have shown that logarithmic molecular proportion ratio (LMPR) diagrams produce straight lines when the the major oxide values of modern day volcanic rocks are used as data. Thus, rocks that do not fit on the lines can be interpreted as being altered. Beswick and Soucie (1978) developed a correction procedure through which original component abundances can

be determined. The method assumes Al_2O_3 immobility. Aluminium does not remain immobile in Archean rocks (Gibson *et al.* 1983; Riverin and Hodgson 1980), although it does not vary as much as other elements. Beswick (1981) has shown that discriminant function analysis in conjunction with LMPR plots can be used to calculate "scores" that assist in the identification of mineralized zones based on the alteration of several components.

The use of molecular proportions (Pearce 1969) and mass balance transfers (Gresens 1967) allow the precise calculation of a component where there has been addition or depletion. Again, these methods assume that at least one component is immobile. Normative mineral calculations have been used in conjunction with mass balance calculations (Gresens 1967) by Knuckey *et al.* (1982), and Riverin and Hodgson (1980) to show which components have been added or subtracted from the rocks, as well as determining volume changes. Normative minerals calculated for unmetamorphosed "Kuroko type" volcanic rocks have been used to determine the original compositions of alteration pipes.

Studemeister (1983) has shown that the ratio of Fe^{+2}/Fe (total) is a good indicator of the oxidation state which prevailed in zones where hydrothermal alteration has occurred.

Gélinas *et al.* (1977) have used normative corundum as an indication of alteration. The presence of corundum indicates that Na, K, Ca, Al, and Si are not present in the correct proportions for formation of normative feldspars. The mobility of components (usually K and Na) are indirectly recognized using this method. Figure 8.22 displays the abundance of normative corundum in the Ben Nevis area, several anomalous zones have been delineated by its high abundances.

Excessive amounts of calcite in a normative mineral calculation within volcanic rocks could indicate that carbonatization had occurred. Figure 8.23 shows the distribution of normative calcite throughout the area. Numerous zones of Ca and CO_2 enrichment are outlined in the figure and indicate some degree of carbonate alteration. However, Ca is notably absent around the Canagau Mines area (see Figure 8.10b), hence normative calcite does not show up in the vicinity of the mine. Figure 8.14a shows the widespread abundance of CO_2 throughout the Canagau Mines area. The CO_2 that cannot form calcite because of the low Ca level probably forms dolomite, magnesite, or siderite. If normative mineral calculations were modified to compute these minerals, then the zone of CO_2 alteration would be more extensive than shown in Figure 8.14b.

The abundance of several other normative minerals can be used to detect various alteration patterns. Minerals such as acmite indicate excess Na, and the undersaturated minerals such as nepheline and leucite indicate silica depletion and alkali enrichment.

Normative minerals that are "expected" in a normative mineral calculation (for example quartz, olivine, albite, and so on) must be used cautiously because their abundance will vary with rock com-

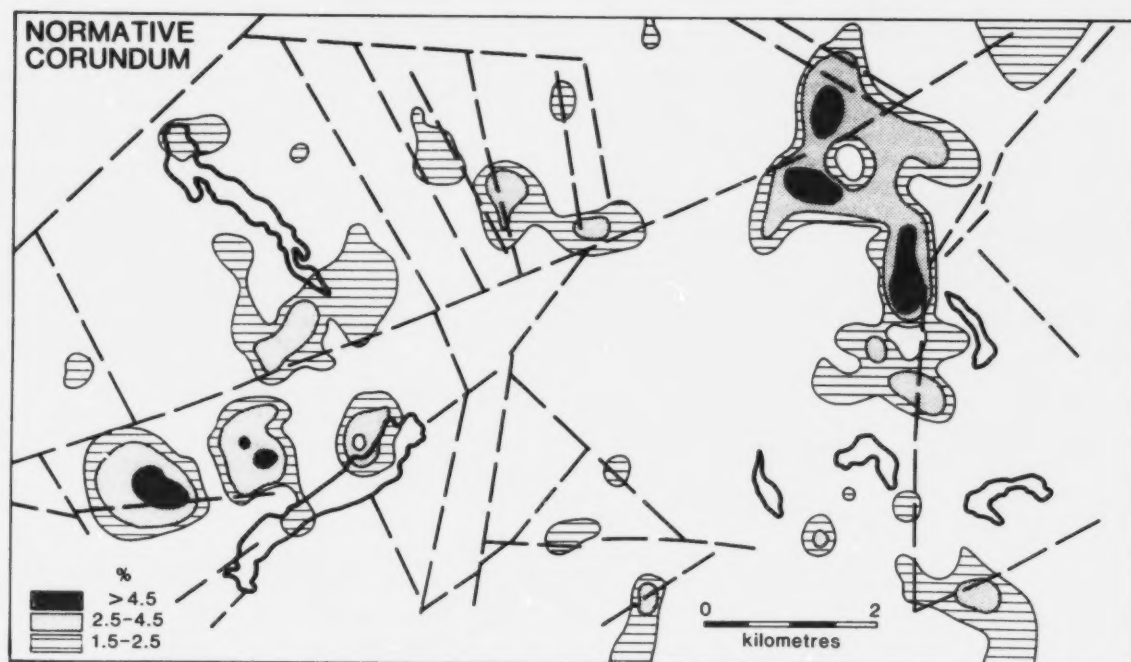


Figure 8.22. Distribution of normative corundum.

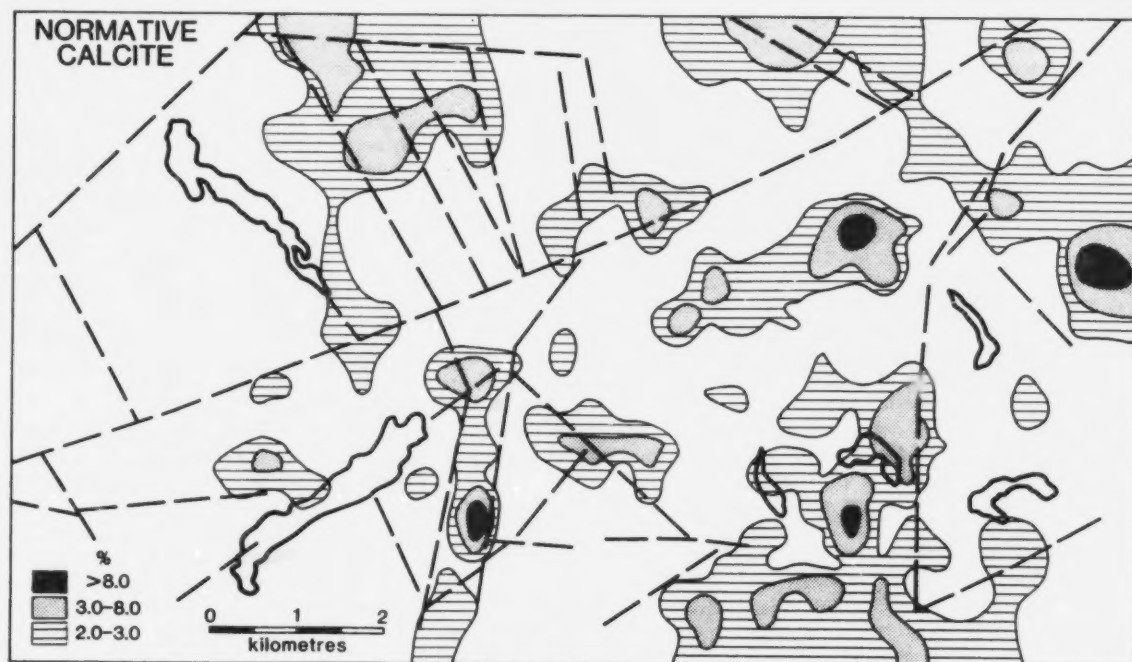


Figure 8.23. Distribution of normative calcite.

position; only carefully calculated residual values would be helpful in delineating altered zones.

STATISTICAL TECHNIQUES

A drawback with methods using either single component or multicomponent residual values is that expected values are required in order to calculate the residual values. Again, the determination of residual values is based on the assumption that the component abundances are normally distributed, and that the classification schemes use immobile components in order to determine residuals. For reasons stated earlier, residual values can be misleading since rocks must first be classified before residuals can be calculated. If the rock is misclassified, then the residual values will be incorrect.

Any method that uses models with the data (that is, comparison of the data with expected values) is subject to scrutiny since such models assume an understanding of the distribution of the data. Techniques such as discriminant function analysis predict the expected behaviour of data based on models. Since the data being used with the discriminant functions may not reflect the same geological process and/or environment as those for which the technique was developed, the resultant residual values may not be significant. For example, if the expected value for a basalt is that typical of a tholeiitic basalt, but the rock that is being tested is in fact calc-alkalic, residual values will mostly reflect the difference between a tholeiitic and a calc-alkalic basalt. Any residual effect due to alteration will probably be masked by this more significant difference.

For these reasons, it was decided that a statistical approach employing a minimum of assumptions regarding expected component values would best distinguish altered from unaltered rocks: Correspondence Analysis is such a technique.

"Correspondence analysis can be viewed as finding the best simultaneous representation of two data sets that compose the rows and columns of a data matrix" (Lebart *et al.* 1984). This means that a matrix consisting of rows of samples and columns of chemical components represent the data matrix from which the simultaneous relationship of variables with samples and samples with variables can be extracted. The details of the method will not be discussed here, but can be found in Lebart *et al.* (1984), Jambu and Lebeaux (1983), David *et al.* (1977), Hill (1975), and Teil (1975). Correspondence analysis was originally developed for contingency tables, which were based on probabilities, that consisted of positive numbers and were used in a variety of applications. Applications of this technique has been carried out in the geological sciences with continuous measurement data by Teil (1975), David *et al.* (1977), and Mellinger (1984).

An aim of correspondence analysis is to represent the data in terms of a number of axes (factors) that describe the distribution of the data. Each factor can be thought of as describing geological processes such as differentiation (partial melting, crystal fractionation, and so on) and alteration in so far as each process produces variation patterns in the data under study. Such processes include carbonatization,

silicification, and alkali depletion. In a suite of unaltered volcanic rocks, there is generally an inverse relationship between (Na, K) and (Ca, Mg, Fe). If the data distribution were governed only by those components, the compositional variation would be dominantly along one axis illustrating a differentiation trend (that is, Harker diagrams). However, if the rocks within a given suite have been altered by some process such as carbonatization then, not only is the data distributed along a direction defining its petrogenesis, but also along an axis that describes the departure of the data by one or more of the affected components (for example CO₂).

In correspondence analysis, the factors are characterized by eigenvectors which determine their orientation in the data space and by eigenvalues which measure how much of the data variation occurs along each factor.

Table 8.1a shows the eigenvalues and percentage contribution of each factor. Note that the first factor accounts for 35.33% of the variation of the data, and the first five factors combined explain 92.86% of the data variation. Table 8.1b lists the computed factor values for each component. Figure 8.24a shows projections of the samples and components onto the first five axes. Table 8.1c gives the contribution of each chemical component over the five computed factors (relative contribution or proximities to the factorial axes/or squared correlations) and the percentage that each component contributes to each factor (absolute contribution/or contributions to the factorial axes inertias). Note that in Table 8.1c, Si, Fe, Mg, Ca, K, and H₂O contribute heavily to the first factor and are the components that define the compositional variation due to magmatic differentiation (see Figure 8.24a). Over 94% of the second factor is defined by the distribution of CO₂ and over 90% of the third factor is defined by the distribution of S. This can be seen in Figures 8.24a and 8.24b.

The ability to plot the component-factor coordinates (R-mode) and the sample factor coordinates (Q-mode) is a unique feature of correspondence analysis. The distribution of the data along the first factor (F1) reflects the compositional variation due to the magmatic trend of volcanic differentiation. The basalts have a greater Ca, Fe, and Mg abundance relative to the rhyolites which are enriched in K; samples plot closest to the components they contain in greater abundance relative to the other samples in the population. As the values along the second factor increase, this reflects an increasing CO₂ content in samples (Figure 24a and 24c). Figure 24c shows the distribution of the altered samples in a projection looking along the compositional line (Factor 1) of the magmatic trend in the F2-F3 plane. The fourth factor (F4) indicates that Ca, Na, and Mg account for most of the variation of the data in that factor. The elements K, Na, and Ca account for most of the variation in the fifth factor (F5) (see Table 8.1c).

Comparison of the relative contributions of the components over the 5 factors in Table 8.1c shows that most of the components are accounted for by F1, the first factor. Only Na, K, Ca, CO₂, and S are mostly accounted for by other factors. The second factor (F2) accounts for over 99% of the CO₂ dis-

TABLE 8.1: CORRESPONDENCE ANALYSES, MAJOR OXIDES.

TABLE 8.1a.

R MODE: VARIABLES	MEAN VALUES	EIGENVALUES	% OF VARIATION (NON TRIVIAL EIGENVALUES)	CUMULATIVE %
SiO ₂	58.56	0.037 787 25	35.32	35.32
Al ₂ O ₃	15.56	0.026 188 00	24.48	59.80
Fe ₂ O ₃	1.74	0.019 762 03	18.47	78.27
FeO	4.74	0.009 276 52	8.67	86.94
MgO	4.10	0.006 328 67	5.92	92.86
CaO	5.68	0.003 012 14	2.82	95.67
Na ₂ O	3.31	0.001 456 05	1.36	97.04
K ₂ O	0.80	0.001 294 54	1.21	98.25
TiO ₂	0.83	0.001 012 32	0.95	99.19
P ₂ O ₅	0.12	0.000 385 18	0.36	99.55
MnO	0.10	0.000 266 72	0.25	99.80
CO ₂	1.32	0.000 155 47	0.15	99.95
S	0.13	0.000 057 44	0.05	100.00
H ₂ O+	2.65			

TABLE 8.1b.

VARIABLE	FACTORS (COORDINATES)				
	1	2	3	4	5
SiO ₂	-0.120 4	-0.016 2	-0.012 3	0.012 3	-0.001 9
Al ₂ O ₃	0.058 4	-0.038 3	-0.013 8	-0.000 8	0.005 9
Fe ₂ O ₃	0.244 4	-0.163 5	0.057 5	-0.015 9	-0.004 3
FeO	0.338 4	0.004 0	0.111 9	-0.115 7	-0.066 5
MgO	0.420 0	-0.021 4	0.033 5	-0.164 2	-0.116 9
CaO	0.382 5	0.035 5	-0.045 6	0.272 4	0.113 8
Na ₂ O	-0.111 3	-0.070 0	-0.120 8	-0.284 7	0.222 5
K ₂ O	-0.560 1	0.178 2	0.191 9	0.201 0	-0.551 0
TiO ₂	0.292 5	-0.047 1	0.001 5	-0.070 0	-0.013 8
P ₂ O ₅	0.219 3	-0.026 6	0.041 7	-0.095 0	-0.016 7
MnO	0.267 7	0.084 5	0.032 3	-0.047 3	-0.051 7
CO ₂	-0.015 7	1.363 5	0.051 4	-0.080 1	0.069 5
S	-0.493 2	-0.304 7	3.774 8	0.059 1	0.554 3
H ₂ O+	0.309 9	0.020 3	0.045 7	-0.041 1	-0.098 8

TABLE 8.1c.

	WEIGHT	ABSOLUTE AND RELATIVE CONTRIBUTIONS									
		AC(1)	RC(1)	AC(2)	RC(2)	AC(3)	RC(3)	AC(4)	RC(4)	AC(5)	RC(5)
SiO ₂	0.587 735	22.54	96.21	0.59	1.75	0.45	1.01	0.96	1.01	0.03	0.02
Al ₂ O ₃	0.156 120	1.41	66.80	0.88	28.77	0.15	3.73	0.00	0.01	0.09	0.69
Fe ₂ O ₃	0.017 417	2.75	66.33	1.78	29.70	0.29	3.67	0.05	0.28	0.01	0.02
FeO	0.047 572	14.41	79.04	0.00	0.01	3.01	8.65	6.87	9.25	3.33	3.06
MgO	0.041 165	19.21	80.69	0.07	0.21	0.23	0.51	11.97	12.34	8.89	6.25
CaO	0.057 007	22.07	61.78	0.27	0.53	0.60	0.88	45.60	31.34	11.68	5.47
Na ₂ O	0.033 195	1.09	7.62	0.62	3.02	2.45	8.98	29.01	49.90	25.98	30.48
K ₂ O	0.008 065	6.70	43.19	0.98	4.37	1.50	5.07	3.51	5.56	38.70	41.80
TiO ₂	0.008 343	1.89	92.14	0.07	2.38	0.00	0.00	0.44	5.27	0.03	0.21
P ₂ O ₅	0.001 178	0.15	80.35	0.00	1.18	0.01	2.90	0.11	15.10	0.01	0.47
MnO	0.001 038	0.20	84.56	0.03	8.42	0.01	1.23	0.02	2.63	0.04	3.15
CO ₂	0.013 271	0.01	0.01	94.22	99.25	0.18	0.14	0.92	0.34	1.01	0.26
S	0.001 260	0.81	1.63	0.45	0.62	90.83	95.66	0.05	0.02	6.12	2.06
H ₂ O+	0.026 632	6.77	87.31	0.04	0.37	0.28	1.90	0.49	1.54	4.11	8.88

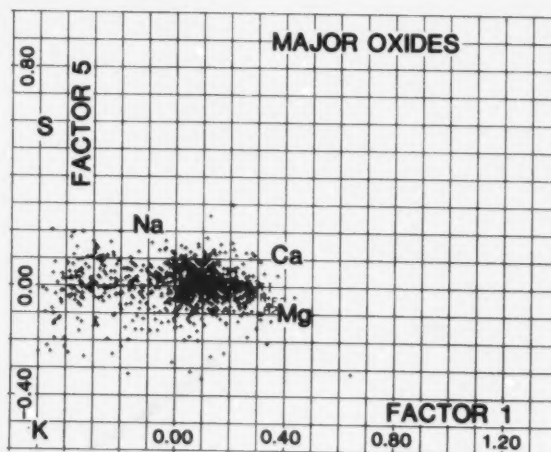
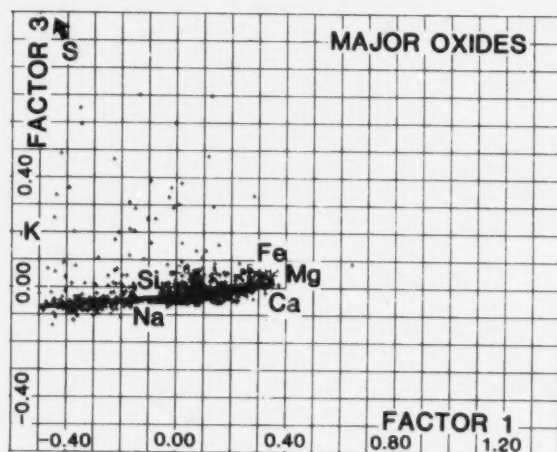
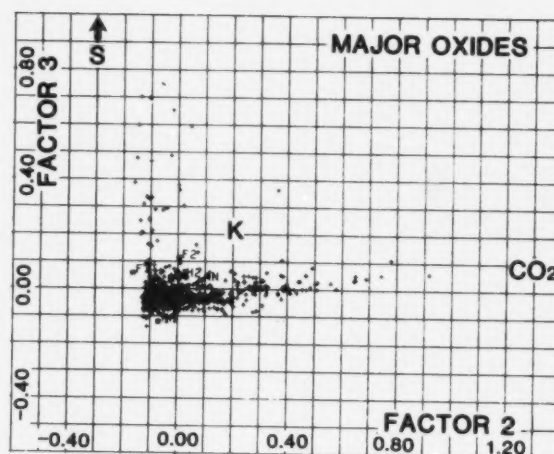
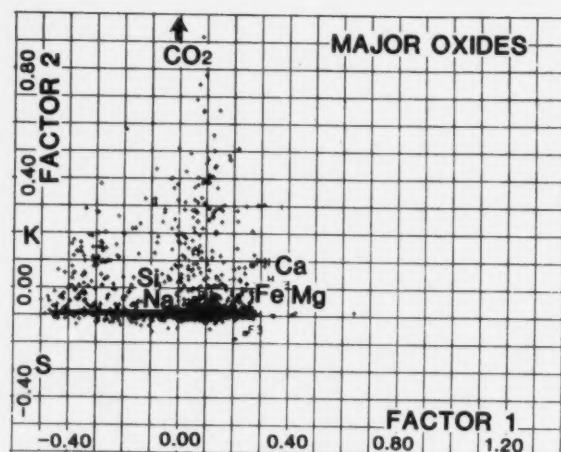
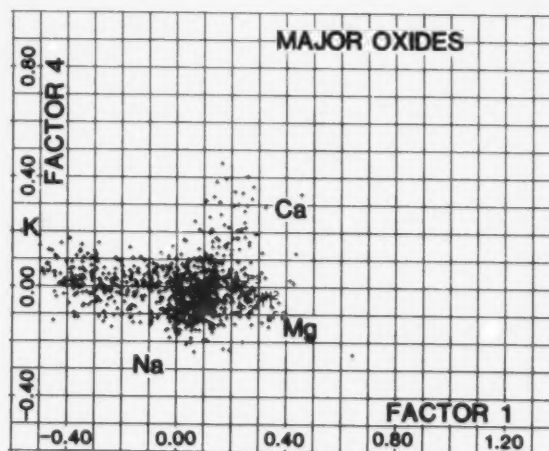


Figure 8.24a to 8.24e. Correspondence analyses, factor scores of samples (+) and chemical components.



tribution and the third factor (F3) accounts for over 95% of the S distribution. The fourth and fifth factors show that Ca, Na, and K, which are generally considered to be the most mobile elements in zones of alteration, are the major contributions.

Figure 8.25 displays contour plots of the first 5 factors for the Ben Nevis area. As described previously, the first factor accounts for the original compositional variation, and this can be seen in Figure 8.25a. The plot closely resembles the lithologic map of the area (Figure 8.2) for example, negative factor values (Figure 8.24a) represent the Na, K-rich samples, most notably the felsic volcanic rocks. Examination of a contour plot of factor 2 (Figure 8.25b) shows that the positive anomalies are coincident with high CO_2 values (see Figure 8.24a). Figure 8.25c shows that the positive anomalies of Factor 3 are the result of the presence of sulphides (see Figure 8.24b); good targets for exploration. Positive Factor 4 values show a tendency towards Ca enrichment (see Figure 8.24d). In Figure 8.25d, positive Factor 4 anomalies are found around the carbonatized zone in the Canagau Mines deposit area. These anomalies represent Ca enrichment around the main zone of carbonatization. Negative Factor 4 anomalies (not shown) indicate Na depletion around the Canagau Mines Property and the Croxall Property. Factor 5 contours in Figure 8.25e show zones of K enrichment associated with negative Factor 5 anomalies (see also Figure 24d). Extremely high values (>0.40) of Factor

5 indicate S enrichment while more moderate values (0.1 to 0.3) indicate Na enrichment.

Correspondence analysis was also applied to the combined major oxides and trace elements. A scaling problem exists between the two groups of components because the major oxides are expressed in weight percent and the trace elements are expressed in parts per million. In order to maintain the proportions of relative abundance within the sample population, the weight percent major oxides were transformed into parts per million.

The results of the combined correspondence analyses are shown in Table 8.2 and in Figure 8.26 and 8.27. The results are nearly identical to those of the major oxides. Part of the reason for this is that the trace elements have small weights relative to the major oxides; however, the trace elements provide additional information and verify what was observed in the isochemical plots. Table 8.2c shows the actual and relative contributions of the components. It is clearly seen from an examination of Table 8.2c and Figure 8.26a that the SiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MgO , CaO , TiO_2 , P_2O_5 , MnO , H_2O^+ , Co , Cr , Ni , V , and Zr distributions are accounted for in the first factor and represent the compatibilities of trace elements that co-exist with the primary magmatic mineralogical phases. This is to be expected because these components are part of the igneous process of compositional variation in volcanic rocks.

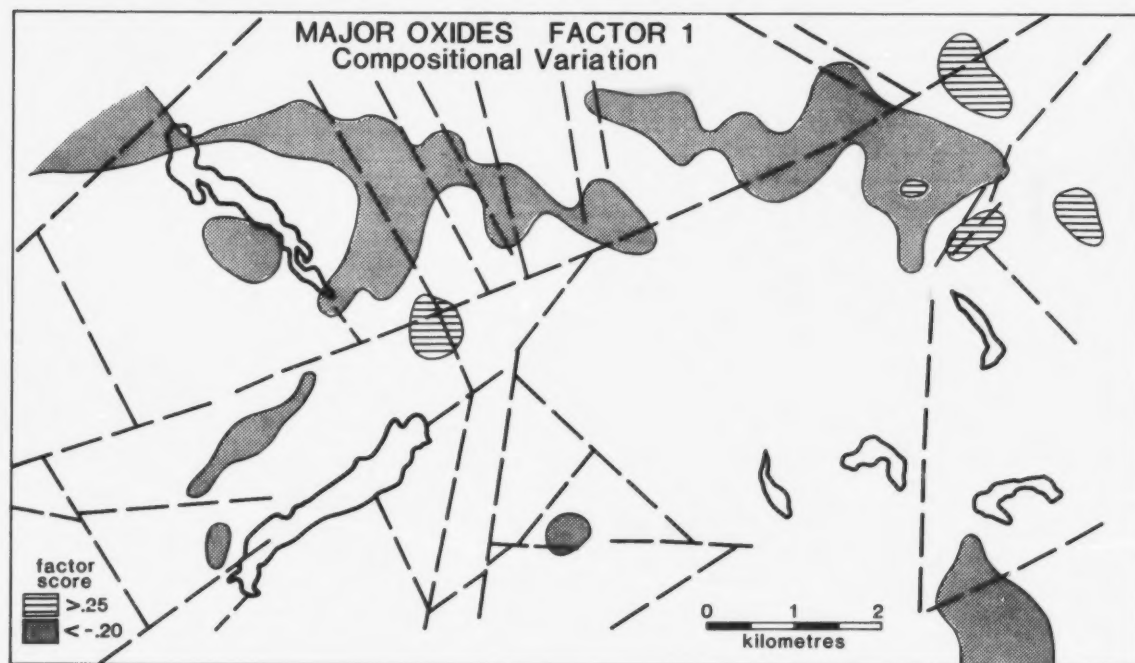


Figure 8.25a. Contour expression of Factor 1 with potassium enriched rocks <-0.20 and mafic rocks >0.25 .

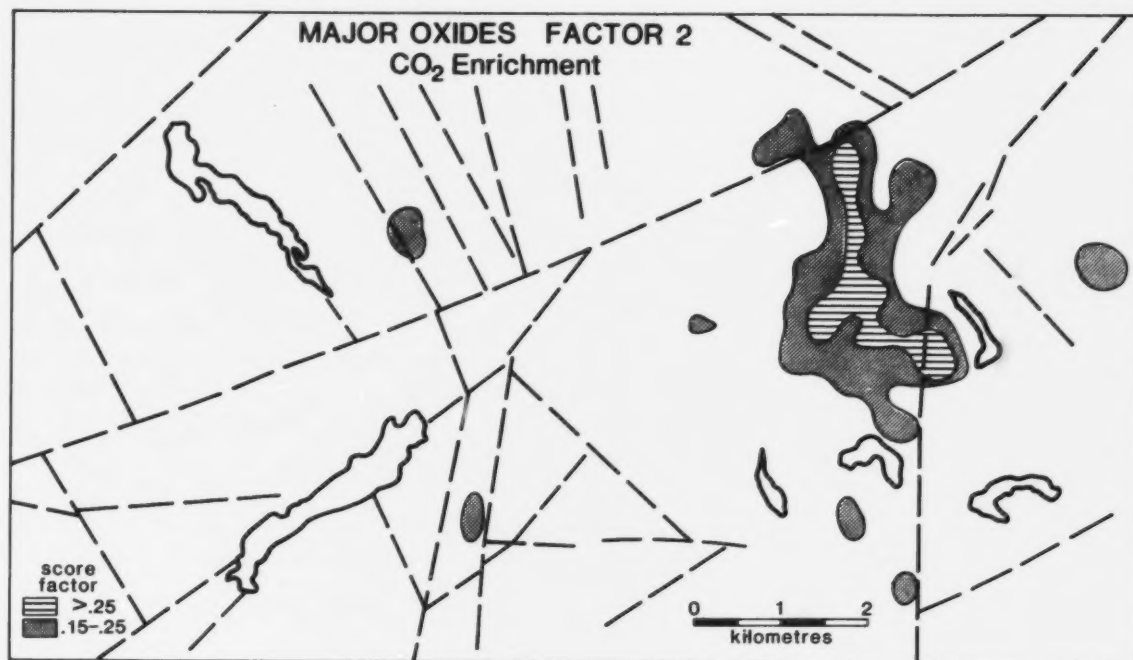


Figure 8.25b. Contour expression of Factor 2 values >0.15 representing carbonatized zones.

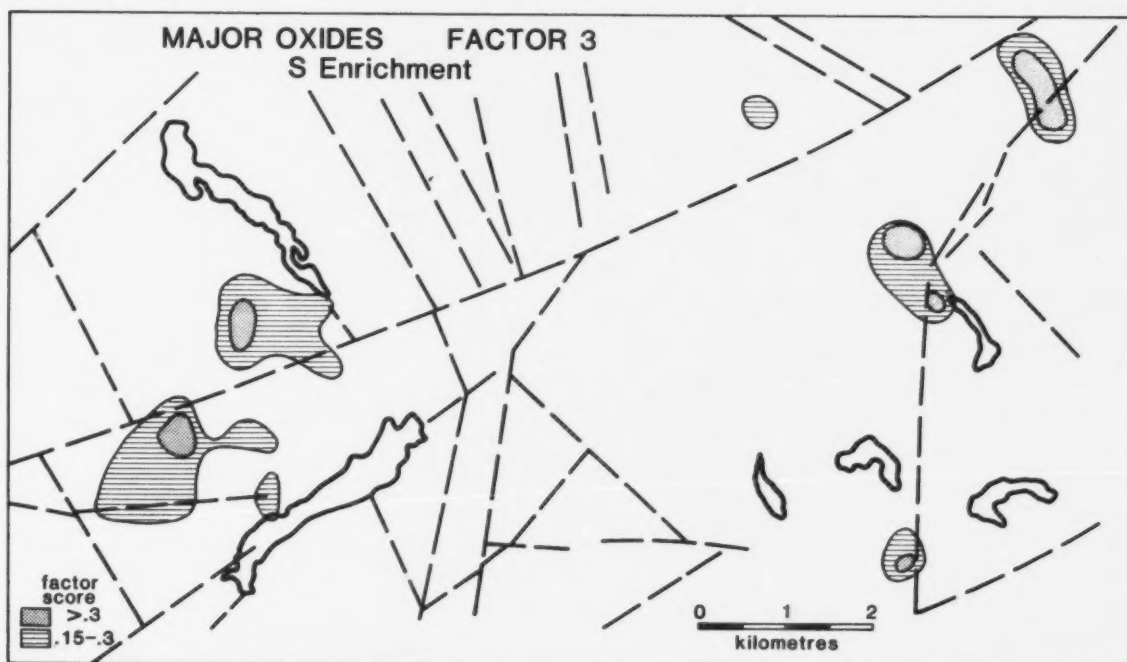


Figure 8.25c. Contour expression of Factor 3 values >0.15 representing areas enriched in sulphur.

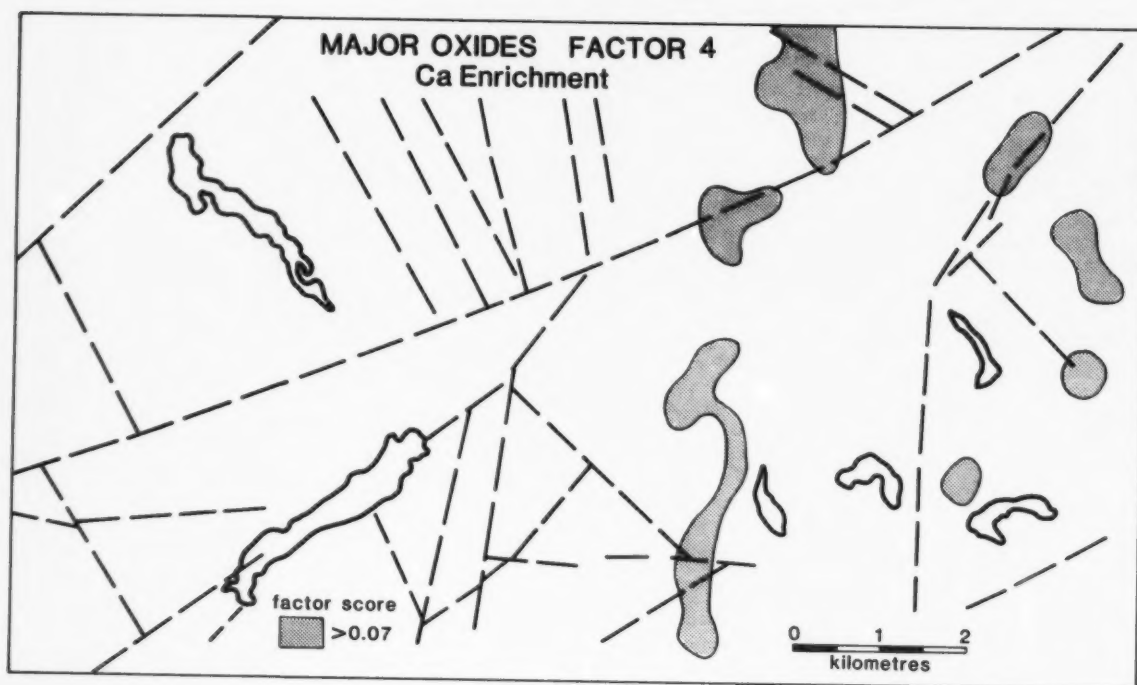


Figure 8.25d. Contour expression of Factor 4 values >0.07 representing rocks anomalously rich in calcium.

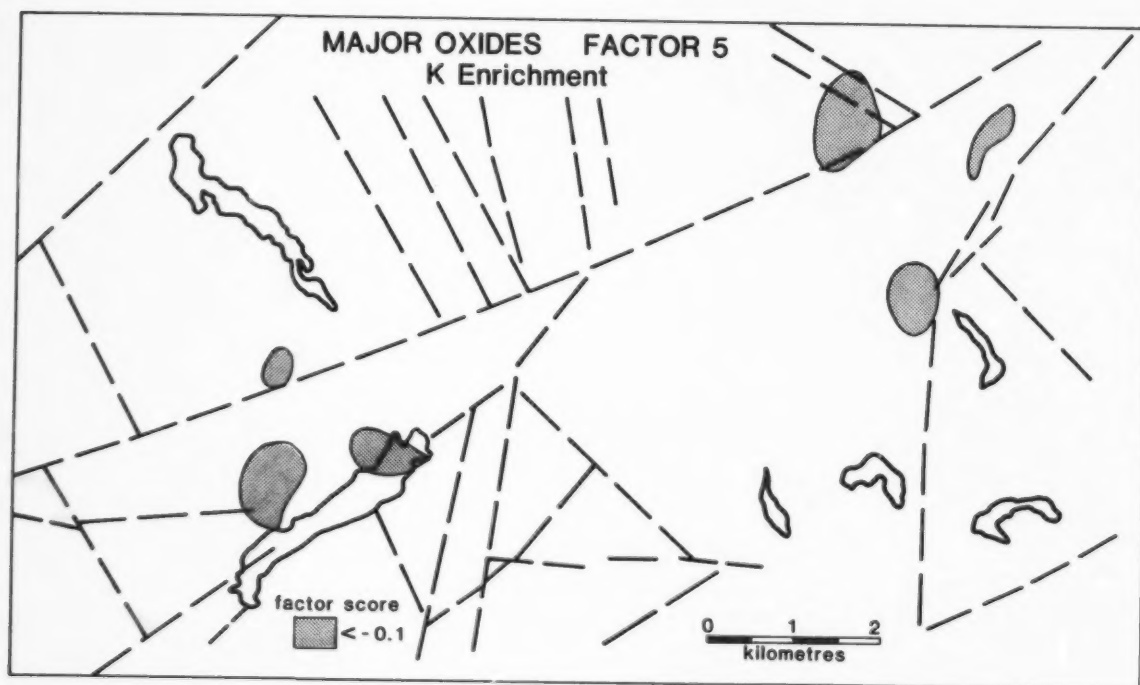


Figure 8.25e. Contour expression of Factor 5 values <-0.1 representing rocks enriched in potassium.

Figures 8.26a, 8.26b, 8.26c, and 8.26d show the samples and components of Factor 1 plotted against the other four. Figure 8.26a clearly shows the compositional variation of the sample population along Factor 1. The addition of the trace elements enhance the compositional line by extension due to the presence of Cr, Ni, and Co at the mafic end of the factor (>0.10), while Ba and Zn occur toward the felsic end of the factor (<-0.10).

Figure 8.27a shows the distribution of the more felsic volcanic rocks in the map area. The actual contributions of components to the second factor is weighted heavily by CO_2 variation as indicated in Table 8.2c. The CO_2 abundance is great. It accounts for 94.18% of the component. From the relative contribution of Factor 2, it can be seen that 55.33% of the Li variation is accounted for by the second factor. The association of CO_2 and Li is well displayed by this factor and is verified by comparison of Figures 8.14b and 8.24b with Figure 8.27b. The pattern in Figure 8.26a is almost identical to that of Figure 8.24a in that the departure of the samples from the main compositional trend line is the same, with enrichment in CO_2 and Li. The second factor obviously outlines the trend line zone of hydrothermal alteration. Also, the first factor shows that nearly 16% of the Li variation is accounted for by the main magmatic trend. This indicates in an indirect way, the relative amount of trace element compatibility that can be explained over the data space.

Factor 3 accounts for the distribution of S and Cu almost exclusively (Table 8.2c). A minor component of Zn associated with S also shows up in the relative contributions column. It is not surprising to see the obvious relationship of Cu and S. Figure 8.26b displays the relationship of Cu and S-enriched samples with the main compositional trend line. Figure 8.27c shows the S-Cu rich areas and as such is a good target for the investigation of sulphide occurrences.

Factor 4 accounts for 31.43% and 49.89% of the CaO and Na_2 variations respectively in Table 8.2c; MgO , TiO_2 and Li are also accounted for in lesser amounts (Table 8.2c). Examination of Figure 8.26d shows that positive Factor 4 values are associated with relative CaO enrichment and negative values are associated with relative Na_2O enrichment. This reflects the inverse relationship of CaO and Na_2O abundances between mafic and felsic volcanic rocks. Thus, it might be expected that positive Factor 4 values outline mafic volcanic rocks and negative Factor 4 values outline felsic volcanic rocks. However, this pattern does not emerge from an examination of Figure 8.27d. This is due to the fact that only 8.63% of the data distribution (Table 8.2a) is defined by Factor 4. The positive anomalies of Figure 8.27c appear to outline zones of CaO enrichment similar to that outlined in the correspondence analysis of the major oxides. Thus, a zone of CaO enrichment around the main zone of carbonatization is delineated. Since the bulk of the sample analyses plotted in Figure 8.26c have Factor 4 values >0.0 , only the extreme negative values outline the zones of Na_2O enrichment.

Factor 5 accounts for only 5.91% of the data distribution (Table 8.2a) and is significantly contributed by Na_2O , K_2 , Ba, and Zn. The association of Na_2O , K_2O , and Zn with alteration is well established through the isochemical plots of Figures 8.11, 8.12, and 8.21. Positive Factor 5 anomalies indicate K_2O , Zn, and Ba enrichment (Figure 8.26e) and both the Croxall Property and Canagau Mines Limited Property anomalies are defined in Figure 8.27e.

Within the distribution of the data over the factors (axes), it can be seen that several "clouds" or groups of sample points occur (Figures 8.24 and 8.26). Some of these groups have an obvious geological interpretation such as those relating to carbonatization or fractionation. It is difficult, however, to "see" some groups of points that may occur along the factor axes which are easily obscured when several groups of data are projected onto a two-dimension plot for visual presentation. A technique for detecting groups of points in n -dimensioned space is that of Dynamic Cluster Analysis. This method was developed by Diday (1973), and is also discussed in Lefebvre and David (1977). The dynamic cluster analysis method works by selecting groups of samples closest to randomly chosen nuclei over the factored space derived from the correspondence analysis. By iteration, the nuclei locations are refined until the locations no longer change and the nuclei represent centres of sample groups.

The results of the dynamic cluster analysis on the major oxide data from Ben Nevis rocks are shown in Figure 8.28a and Table 8.3. Figure 8.28a outlines the spatial positioning of the groups; Table 8.3a shows the factor space coordinate of the groups as well as the mean composition and standard deviation of each component for each group. The mean compositions and standard deviations allow the analyst to determine which components define to the uniqueness of each group. Dynamic cluster analysis identified 28 groupings based on the factor coordinates of the groups. Each of these groups reflects some geological process. Groups 1 and 2 represent the mafic volcanic rocks (Table 8.3b). Groups 7, 8, 9, 12, 14, 13, 17, and 27 contain anomalous CO_2 . These groups, when spatially plotted (Figure 8.28b and e), show the progressive increase of CO_2 within the main zone of carbonatization in the eastern part of Ben Nevis Township. Groups 11, 20, 21, 22, 23, 26, and 28 indicate increasing S within the sample population. The reader should realize that not all groups could be on the figures because of space problems. It is noteworthy that Group 11 (Figure 8.28 a, c, e) represents 17 samples. Of these 17 samples, 14 are from the Croxall Property area in western Ben Nevis Township and represent significant S enrichment.

The 18 samples in Group 10 are significant because of their high Ca values. These samples are from around the main zone of carbonatization and may reflect a chemical zoning effect of Ca enrichment away from the main zone of hydrothermal circulation (Figure 28d). Groups 7, 8, 14, and 17, which are associated with CO_2 enrichment, are also slightly depleted in Ca relative to other groups.

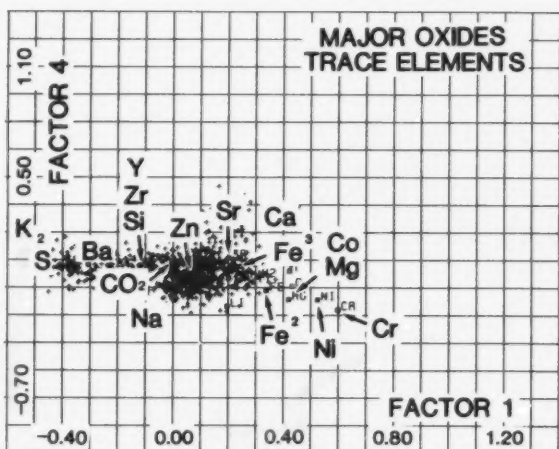
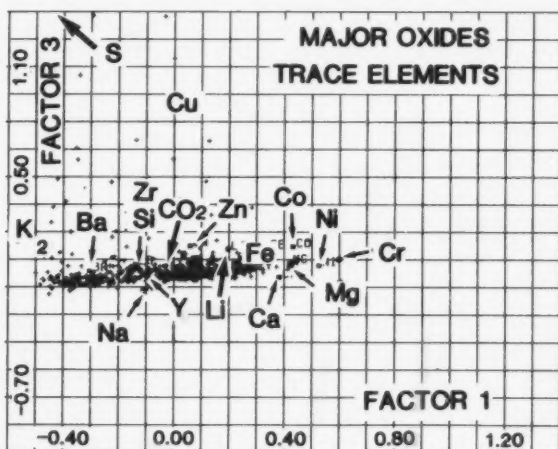
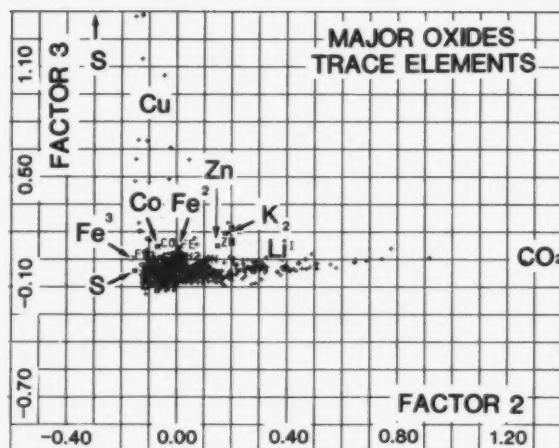
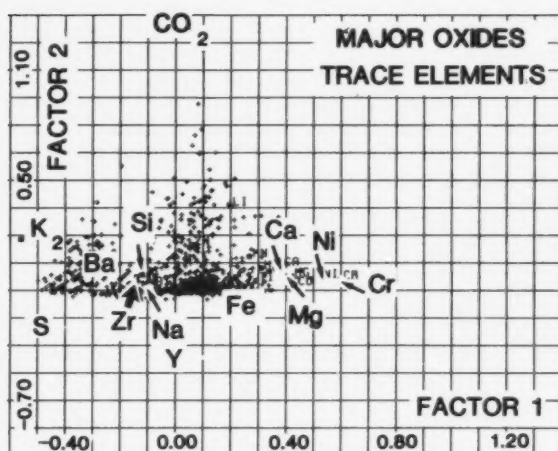
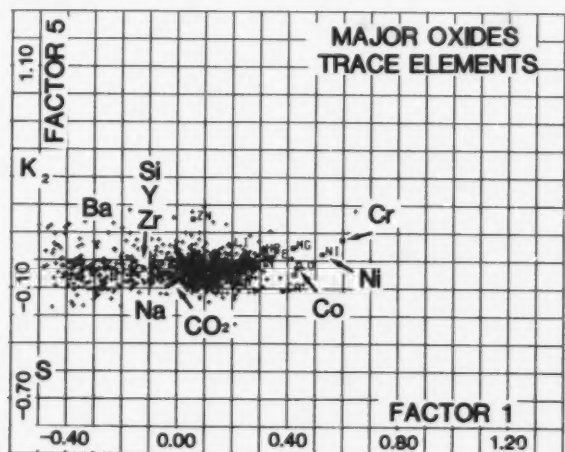


Figure 8.26a to 8.26e. Correspondence analyses, factor scores of samples (+) and chemical components.



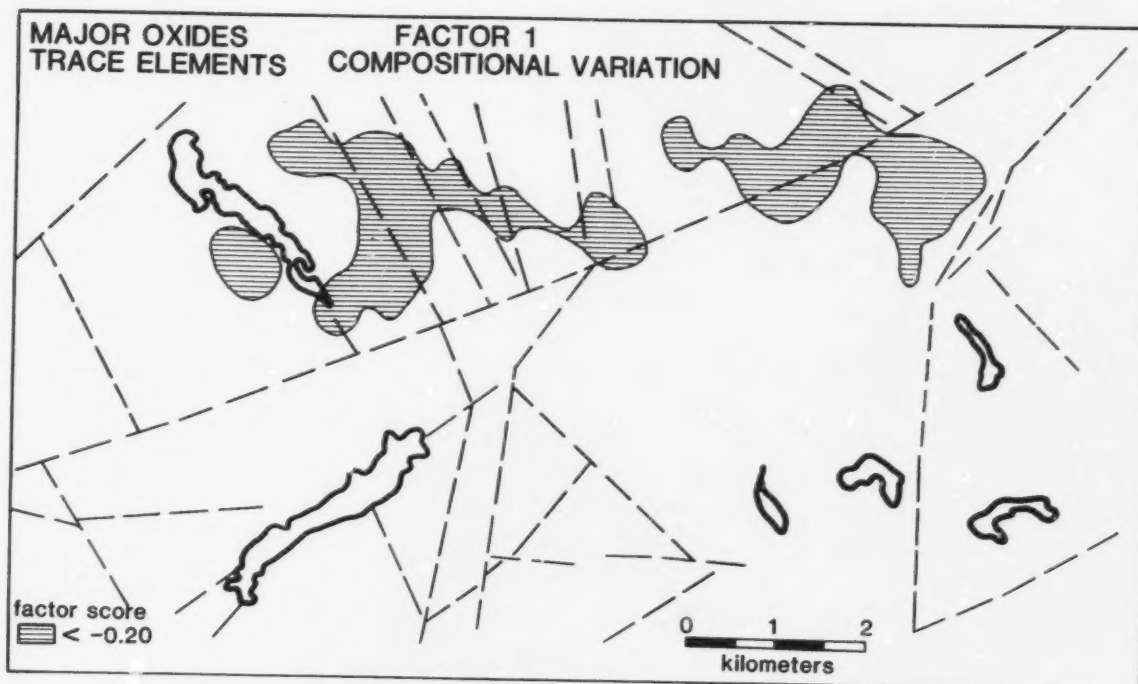


Figure 8.27a. Negative anomalies outline sodium, potassium, barium-enriched felsic volcanic rocks.

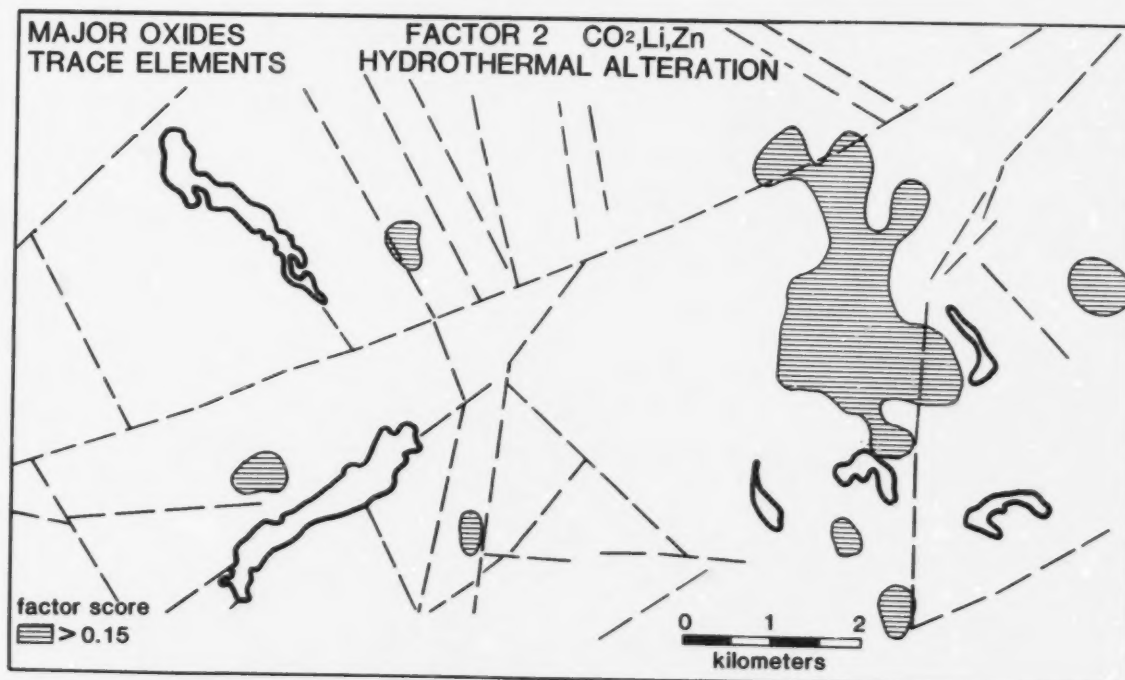


Figure 8.27b. Positive anomalies outline CO₂, Li, Zn enriched areas.

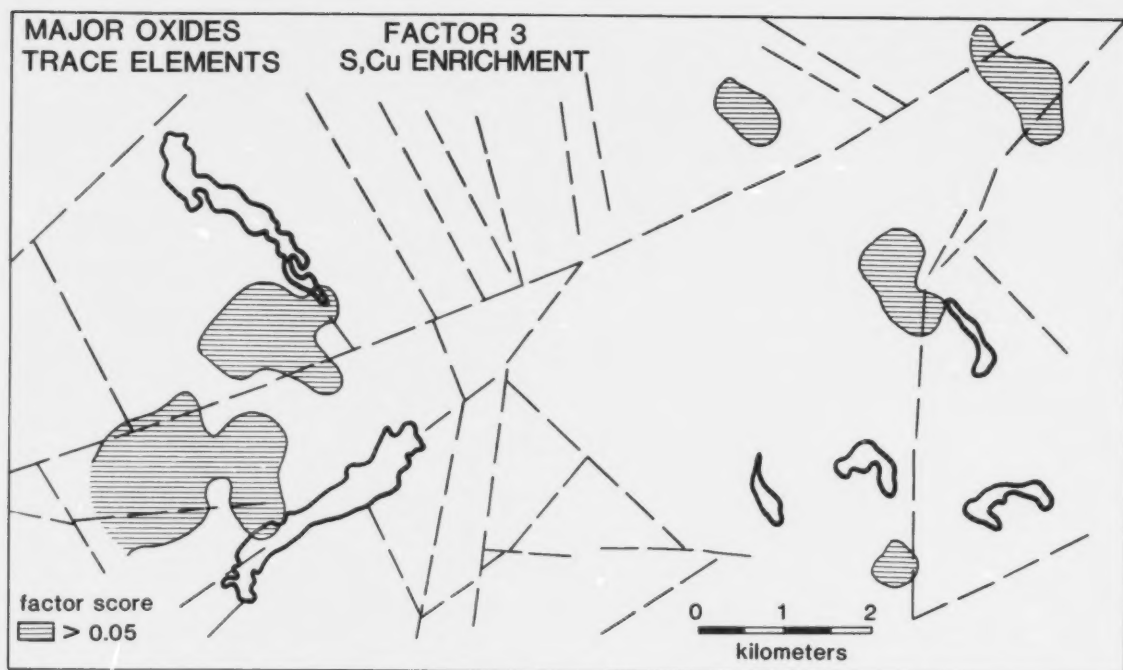


Figure 8.27c. Positive anomalies indicate Cu, S rich zones (sulphide mineralization).

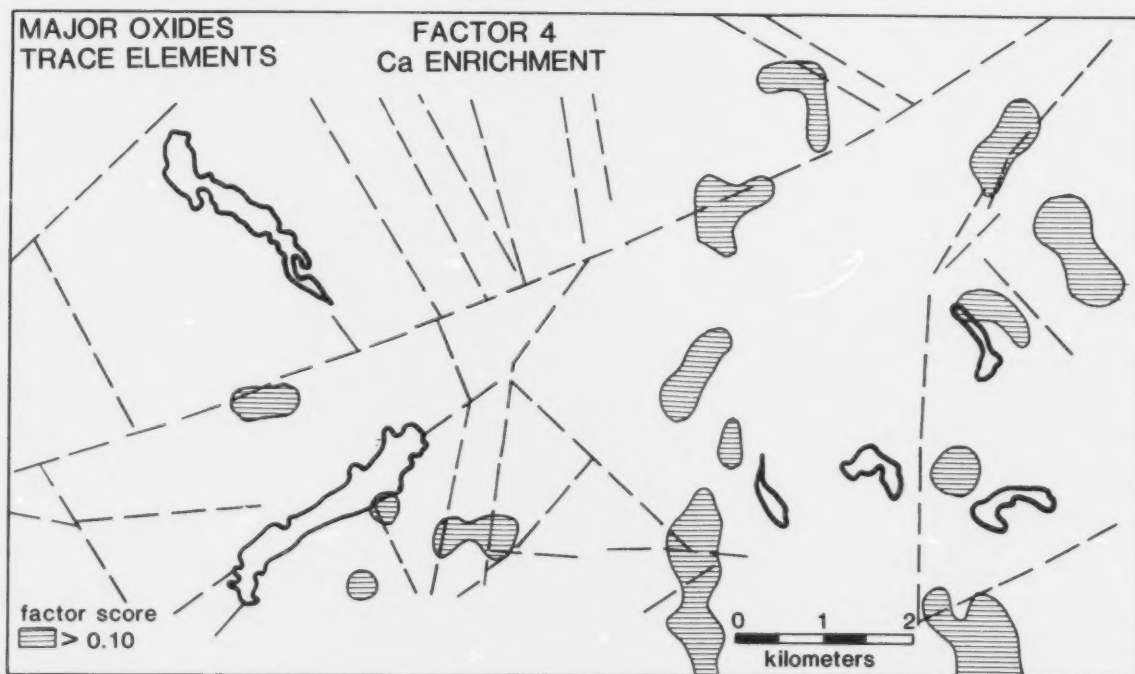


Figure 8.27d. Positive anomalies indicate Ca enriched zones. Note the band of Ca enrichment around the carbonated area. Compare with Figure 8.27b.

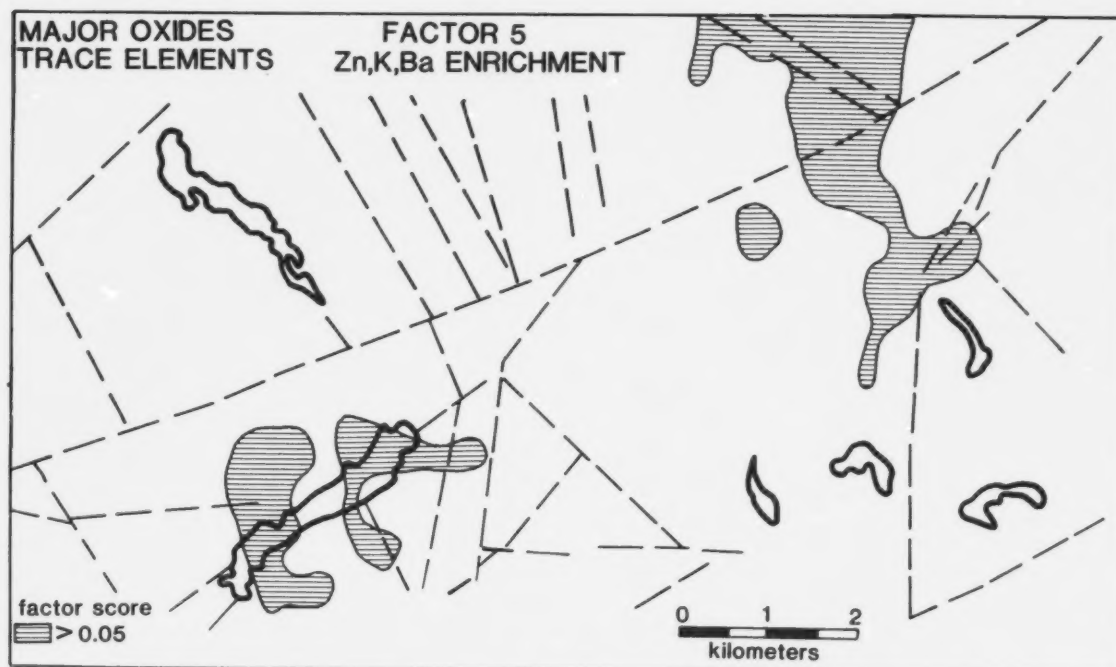


Figure 8.27e. Positive anomalies indicate Zn, K, Ba enriched zones.

TABLE 8.2: CORRESPONDENCE ANALYSIS, MAJOR OXIDES AND TRACE ELEMENTS.

TABLE 8.2a. OXIDES AND TRACE ELEMENTS.

R MODE: VARIABLES	MEAN VALUES	EIGENVALUES	% OF VARIATION (NON TRIVIAL EIGENVALUES)	CUMULATIVE %
SiO ₂	585 593.55	0.03 786 090	35.21	35.21
Al ₂ O ₃	155 551.22	0.02 617 004	24.34	59.55
Fe ₂ O ₃	17 354.01	0.01 978 271	18.40	77.95
FeO	47 398.54	0.00 927 626	8.63	86.58
Mgo	41 015.45	0.00 635 597	5.91	92.49
CaO	56 799.15	0.00 304 222	2.83	95.32
Na ₂ O	33 074.45	0.00 146 906	1.37	96.68
K ₂ O	8 035.89	0.00 130 136	1.21	97.89
TiO ₂	8 312.53	0.00 101 779	0.95	98.84
P ₂ O ₅	1 173.97	0.00 038 944	0.36	99.20
MnO	1 034.31	0.00 026 862	0.25	99.45
CO ₂	13 222.87	0.00 016 093	0.15	99.60
S	1 255.11	0.00 013 438	0.12	99.73
H ₂ O+	26 535.04	0.00 009 840	0.09	99.82
Ba	208.11	0.00 005 193	0.05	99.87
Co	22.61	0.00 003 896	0.04	99.90
Cr	85.37	0.00 003 444	0.03	99.94
Cu	56.18	0.00 002 528	0.02	99.96
Li	17.01	0.00 002 042	0.02	99.98
Ni	78.88	0.00 001 446	0.01	99.99
Zn	88.78	0.00 000 386	0.00	99.99
Sr	135.11	0.00 000 241	0.00	100.00
V	131.40	0.00 000 220	0.00	100.00
Y	24.13	0.00 000 093	0.00	100.00
Zr	132.48			

TABLE 8.2b.

VARIABLE	FACTORS (COORDINATES)				
	1	2	3	4	5
SiO ₂	-0.120 5	-0.016 3	-0.012 4	0.012 2	0.001 7
Al ₂ O ₃	0.058 3	-0.038 2	-0.013 9	-0.000 6	-0.005 8
Fe ₂ O ₃	0.244 4	-0.163 3	0.057 4	0.016 2	0.004 5
FeO	0.338 3	0.004 4	0.111 6	-0.115 4	0.066 5
MgO	0.420 1	-0.020 9	0.033 2	-0.164 2	0.116 8
CaO	0.382 1	0.035 9	-0.045 8	0.272 8	-0.113 6
Na ₂ O	-0.111 1	-0.070 2	-0.120 8	-0.284 5	-0.222 3
K ₂ O	-0.560 9	0.177 8	0.192 4	0.201 0	0.551 9
TiO ₂	0.292 5	-0.046 7	0.001 4	-0.069 6	0.013 9
P ₂ O ₅	0.219 2	-0.026 3	0.041 5	-0.094 8	0.017 0
MnO	0.267 6	0.084 8	0.032 1	-0.047 1	0.051 8
CO ₂	-0.017 2	1.363 4	0.051 8	-0.079 9	-0.070 4
S	-0.491 2	-0.306 7	3.774 2	-0.058 8	-0.554 4
H ₂ O+	0.309 7	0.020 7	0.045 5	-0.040 9	0.098 5
Ba	-0.304 3	0.047 6	-0.012 3	0.063 7	0.334 7
Co	0.432 0	-0.068 9	0.119 9	-0.091 3	0.008 1
Cr	0.597 7	-0.036 4	0.051 0	-0.220 9	0.161 7
Cu	0.030 6	-0.092 7	0.881 4	0.051 5	-0.071 1
Li	0.196 1	0.364 9	0.107 0	-0.202 5	0.128 9
Ni	0.525 3	-0.027 1	0.018 5	-0.166 3	0.084 4
Zn	0.058 7	0.149 2	0.124 2	-0.022 5	0.272 6
Sr	0.203 1	-0.151 2	-0.011 7	0.062 0	-0.083 3
V	0.423 2	-0.066 1	0.004 7	-0.008 9	-0.024 3
Y	-0.095 3	-0.051 6	-0.020 6	0.002 4	-0.020 4
Zr	-0.140 0	-0.026 3	0.023 3	-0.006 8	0.030 9

TABLE 8.2c.

	WEIGHT	ABSOLUTE AND RELATIVE CONTRIBUTIONS									
		AC(1)	RC(1)	AC(2)	RC(2)	AC(3)	RC(3)	AC(4)	RC(4)	AC(5)	RC(5)
SiO ₂	0.587 158	22.51	96.22	0.60	1.77	0.45	1.01	0.94	0.99	0.03	0.02
Al ₂ O ₃	0.155 967	1.40	66.77	0.87	28.77	0.15	3.78	0.00	0.01	0.08	0.67
Fe ₂ O ₃	0.017 400	2.75	66.40	1.77	29.63	0.29	3.66	0.05	0.29	0.01	0.02
FeO	0.047 525	14.37	79.11	0.00	0.01	2.99	8.61	6.83	9.21	3.31	3.06
MgO	0.041 125	19.17	80.73	0.07	0.20	0.23	0.50	11.95	12.33	8.82	6.24
CaO	0.056 951	21.97	61.69	0.28	0.54	0.60	0.89	45.68	31.43	11.55	5.45
Na ₂ O	0.033 163	1.08	7.61	0.62	3.04	2.45	8.99	28.94	49.89	25.79	30.47
K ₂ O	0.008 057	6.69	43.20	0.97	4.34	1.51	5.08	3.51	5.55	38.61	41.83
TiO ₂	0.008 335	1.88	92.22	0.07	2.35	0.00	0.00	0.43	5.21	0.03	0.21
P ₂ O ₅	0.001 177	0.15	80.43	0.00	1.16	0.01	2.89	0.11	15.04	0.01	0.48
MnO	0.001 037	0.20	84.50	0.03	8.49	0.01	1.22	0.02	2.62	0.04	3.17
CO ₂	0.013 258	0.01	0.02	94.18	99.24	0.18	0.14	0.91	0.34	1.03	0.26
S	0.001 258	0.80	1.62	0.45	0.63	90.62	95.66	0.05	0.02	6.09	2.06
H ₂ O+	0.026 606	6.74	87.36	0.04	0.39	0.28	1.89	0.48	1.52	4.06	8.84
Ba	0.000 209	0.05	43.85	0.00	1.08	0.00	0.07	0.01	1.92	0.37	53.08
Co	0.000 023	0.01	87.15	0.00	2.22	0.00	6.71	0.00	3.89	0.00	0.03
Cr	0.000 086	0.08	81.92	0.00	0.30	0.00	0.60	0.05	11.19	0.04	5.99
Cu	0.000 056	0.00	0.12	0.00	1.08	0.22	97.83	0.00	0.33	0.00	0.64
Li	0.000 017	0.00	15.98	0.01	55.33	0.00	4.76	0.01	17.03	0.00	6.90
Ni	0.000 079	0.06	88.50	0.00	0.23	0.00	0.11	0.02	8.87	0.01	2.29
Zn	0.000 089	0.00	2.97	0.01	19.20	0.01	3.30	0.00	0.44	0.10	64.09
Sr	0.000 135	0.01	54.98	0.01	30.47	0.00	0.18	0.01	5.12	0.01	9.25
V	0.000 132	0.06	97.25	0.00	2.37	0.00	0.01	0.00	0.04	0.00	0.32
Y	0.000 024	0.00	72.12	0.00	21.14	0.00	3.38	0.00	0.05	0.00	3.32
Zr	0.000 133	0.01	89.77	0.00	3.16	0.00	2.48	0.00	0.21	0.00	4.38

Trace elements were also used in conjunction with major oxides for the dynamic cluster analysis. Figure 8.29a shows the spatial position of some of the groups delineated by the dynamic cluster analysis along the factor axes. Figure 8.29b shows the distribution of the groups over the Ben Nevis area, and Table 8.4 lists the factor coordinate positions and mean abundances for each component of each group. Groups 2, 3, and 4 contain most of the mafic volcanic rocks; Groups 5, 6, 10, and 12 include intermediate to felsic volcanic rocks (Table 8.4). Groups 7 and 8 are enriched in Zn, Li, CO_2 , S and K (Figure 8.29b and d) and represent samples around the altered areas of the Croxall Property and the Canagau Mines Deposit (Figure 8.29a). Group 11 contains S and Cu enriched samples that occur at the Canagau Mines Deposit and Croxall Property as well as some isolated sulphide enriched samples (Figure 8.29c). Group 6 represents Cr, Ni, enriched samples associated with mafic intrusive and tholeiitic volcanic rocks of the area. Group 10 represents rocks of the Ca enriched zone, similar to Group 10 in the previous analysis using major oxides. The progressive CO_2 enrichment that was clearly shown by Groups 7, 8, and 14 in the major oxides analysis also show up when the major oxides and trace elements are combined. Thus, trace elements reflect and/or enhance the analysis of the major oxides.

CONCLUSIONS

When using any technique for locating mineralized areas, it is essential to select the proper components in order to locate anomalous zones. Chemical compounds such as SiO_2 , Al_2O_3 , MgO , TiO_2 , Ni, Co, Cr, V, and Zn are all very useful indicators for discriminating rock types due to their variation associated with fractionation in calc-alkalic suites. In hydrothermal systems, certain components are known to be mobile and these components are desirable indicators when searching for altered rocks. In the Ben Nevis area, certain major oxides and trace elements were noted for such characteristics. For hydrothermal systems, Na, K, Ca, CO_2 , F, Zn, B, As, and Li are useful indicators of alteration.

Several oxides and some trace elements are useful indicators of mineralization; Factors 2 and 3 from the correspondence analysis summarize the effects of the major element and trace element alteration around the Ben Nevis area. Dynamic cluster analysis can assist in identifying groups of data related to S enrichment (Croxall Property) or carbonatization (Canagau Mines Deposit) which were not readily apparent after correspondence analysis alone.

It is important to have a full understanding of the geological complexities of an area to best interpret lithogeochemical information. A mixture of chemical environments (that is, calc-alkalic and tholeiitic rocks) would make interpretation of the Ben Nevis data more difficult; certain critical components may not be as useful in discriminating zones of alteration under those circumstances.

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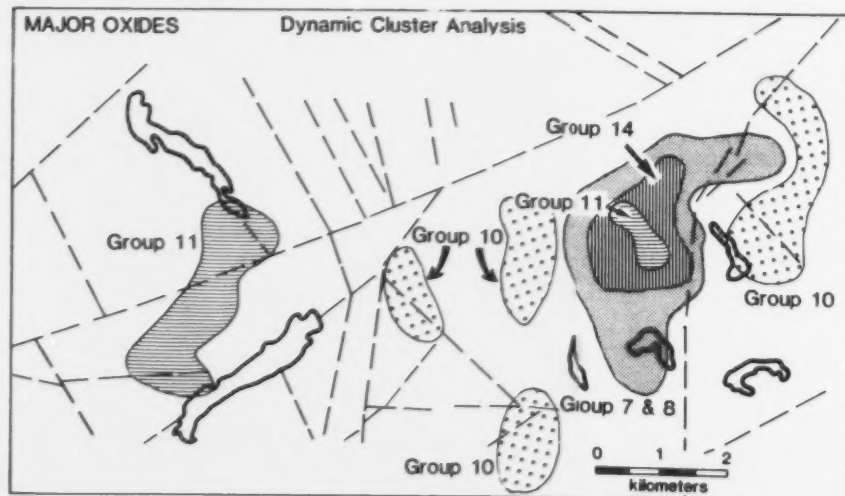


Figure 8.28a. Geographic presentation of some of the groups computed from the Dynamic Cluster Analysis in the Ben Nevis area.

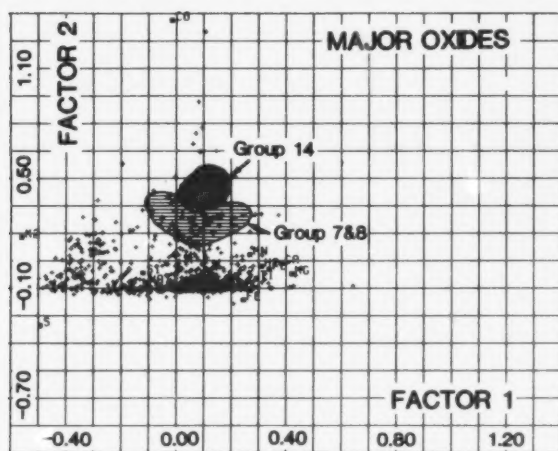


Figure 8.28b. Locations of Groups 7, 8, and 14 in the factor space.

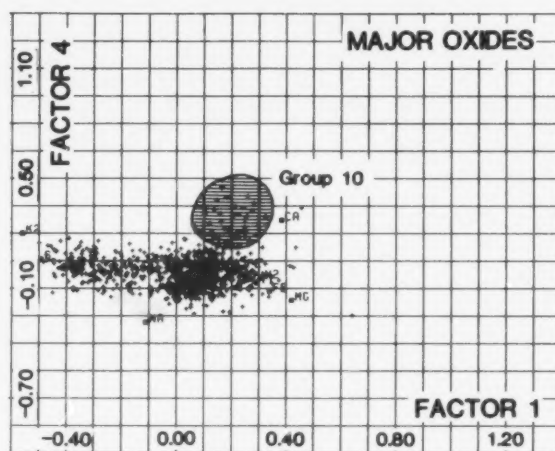


Figure 8.28d. Location of Group 10 in the factor space.

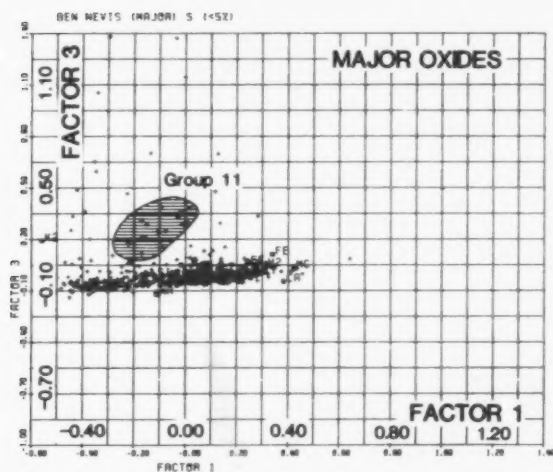


Figure 8.28c. Location of Group 11 in the factor space.

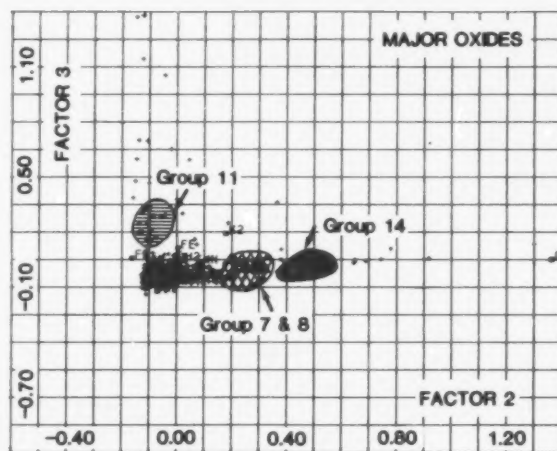


Figure 8.28e. More locations of Groups 7, 8, 11, and 14 in the factor space.

TABLE 8.3: DYNAMIC CLUSTER NUCLEI AND AVERAGE COMPOSITIONS OF EACH CLUSTER.

TABLE 8.3a. MEAN SCORES OF THE GROUPS.

GROUP	SIZE	FACTORS				
		1	2	3	4	5
1	119	0.143 9	-0.075 1	-0.015 9	-0.018 6	-0.013 5
2	143	0.030 1	-0.090 8	-0.036 7	-0.060 2	0.018 5
3	85	0.128 2	-0.065 2	-0.023 6	0.107 5	0.025 8
4	56	-0.154 5	-0.086 5	-0.042 4	-0.007 3	0.008 1
5	37	-0.374 7	-0.044 3	-0.069 9	0.008 9	0.008 4
6	46	0.268 7	-0.079 1	0.011 2	-0.032 3	-0.064 7
7	31	0.089 7	0.250 2	0.008 0	-0.090 1	0.004 8
8	19	0.016 9	0.327 4	0.003 9	0.031 5	-0.034 1
9	44	-0.316 9	0.120 6	-0.053 3	0.042 3	0.022 3
10	23	0.223 8	-0.011 1	-0.035 8	0.307 4	0.085 3
11	17	-0.146 9	-0.087 1	0.219 8	-0.023 9	0.044 5
12	45	0.034 4	0.099 6	-0.023 7	-0.101 2	0.057 3
13	8	0.103 1	0.653 2	0.055 5	0.004 0	-0.093 7
14	27	0.153 6	0.404 5	0.011 8	-0.025 4	0.039 2
15	16	-0.401 7	-0.062 8	-0.011 2	0.065 9	-0.175 3
16	30	-0.039 7	-0.052 9	-0.005 6	0.053 0	-0.117 4
17	17	-0.183 2	0.195 0	0.007 6	0.067 0	-0.101 9
18	27	-0.291 0	-0.074 0	-0.084 0	-0.072 6	0.097 8
19	8	0.083 0	0.003 4	0.072 9	-0.074 7	-0.247 5
20	3	-0.209 0	-0.131 1	1.378 6	-0.009 1	0.137 7
21	8	-0.311 2	0.041 4	0.411 8	0.120 8	-0.127 0
22	7	0.025 5	-0.105 0	0.521 7	-0.018 6	0.124 0
23	1	0.209 6	-0.184 3	1.467 7	-0.004 8	0.296 8
24	1	-0.193 8	0.579 0	0.004 6	0.042 0	-0.026 0
25	1	0.641 2	-0.086 7	0.086 2	-0.246 3	-0.317 8
26	1	-0.000 5	-0.124 4	1.144 9	-0.127 1	-0.054 9
27	1	0.108 1	1.300 3	0.134 1	0.314 2	0.118 9
28	1	-0.340 6	-0.044 5	1.054 0	0.106 9	0.003 5

TABLE 8.3b: DYNAMIC CLUSTER ANALYSIS: GROUP DESCRIPTION.

GROUP	SiO ₂	S.D.	Al ₂ O ₃	MEAN VALUES & STANDARD DEVIATIONS (S.D.)				FeO	S.D.	MgO	S.D.	CaO	S.D.
				S.D.	Fe ₂ O ₃	S.D.	FeO						
1	53.88	1.73	16.28	0.96	2.24	0.41	6.07	0.77	5.64	0.61	6.82	1.01	
2	57.48	2.18	16.29	1.22	1.88	0.47	4.98	0.82	4.75	0.85	5.19	1.08	
3	55.10	2.18	16.81	1.13	2.03	0.40	4.92	0.76	4.23	0.79	8.92	1.17	
4	64.06	2.42	15.83	1.44	1.66	0.43	3.15	0.70	2.73	0.85	3.92	1.21	
5	73.30	2.73	13.56	1.04	0.89	0.46	1.54	0.68	0.65	0.25	1.83	0.69	
6	50.07	2.47	16.00	1.48	2.57	0.28	7.74	0.95	7.34	1.38	7.53	1.58	
7	53.35	2.27	15.17	0.81	1.40	0.37	5.91	0.79	5.35	0.66	5.46	0.65	
8	55.68	3.45	14.75	1.59	1.13	0.38	5.00	0.99	3.84	0.99	6.57	1.03	
9	71.00	3.23	12.80	1.40	0.82	0.48	1.95	0.79	0.78	0.37	3.22	0.84	
10	53.56	3.36	16.34	1.46	2.17	0.36	4.42	1.06	3.29	0.98	13.78	1.57	
11	63.07	6.20	15.04	2.14	1.99	0.37	3.64	2.00	3.38	1.72	3.42	1.69	
12	56.04	2.07	15.56	0.89	1.65	0.52	5.15	0.77	4.59	0.78	4.98	1.33	
13	50.45	1.55	14.18	1.07	0.93	0.35	6.10	0.96	5.39	0.94	6.79	0.78	
14	50.64	3.50	14.41	1.28	1.33	0.75	6.29	1.18	5.19	0.88	7.84	2.10	
15	76.54	3.54	12.28	1.71	0.83	0.42	2.03	1.28	1.28	0.89	0.57	0.48	
16	59.00	3.18	16.47	1.19	1.77	0.36	4.38	0.72	4.01	0.97	5.34	1.62	
17	63.82	4.62	14.67	2.01	0.95	0.33	3.34	0.92	2.27	0.67	4.11	0.72	
18	68.84	3.49	15.21	1.42	1.03	0.58	2.28	0.87	1.20	0.59	2.16	0.82	
19	53.76	2.54	16.88	1.16	1.91	0.48	7.44	1.33	6.03	0.88	3.02	2.09	
20	60.58	9.94	12.48	4.37	1.76	0.16	7.28	0.32	3.75	1.78	1.83	2.40	
21	68.33	8.42	13.31	1.82	1.84	0.32	2.91	1.76	1.60	0.89	2.19	2.03	
22	54.82	5.61	15.82	1.05	2.40	0.28	5.91	2.16	4.80	1.06	5.66	2.78	
23	39.92	0.0	15.35	0.0	2.61	0.0	14.94	0.0	2.48	0.0	7.65	0.0	
24	56.74	0.0	16.78	0.0	0.91	0.0	3.40	0.0	1.36	0.0	4.99	0.0	
25	42.69	0.0	9.54	0.0	2.17	0.0	11.10	0.0	19.41	0.0	7.48	0.0	
26	52.12	0.0	15.70	0.0	2.41	0.0	11.57	0.0	4.56	0.0	0.38	0.0	
27	46.48	0.0	10.21	0.0	0.17	0.0	2.05	0.0	3.81	0.0	15.56	0.0	
28	67.01	0.0	11.53	0.0	1.97	0.0	5.31	0.0	1.43	0.0	1.76	0.0	

TABLE 8.3b: CONTINUED.

GROUP	Na ₂ O	MEAN VALUES & STANDARD DEVIATIONS (S.D.)										H ₂ O+	S.D.		
		S.D.	K ₂ O	S.D.	TiO ₂	S.D.	P ₂ O ₅	S.D.	MnO	S.D.	CO ₂			S	S.D.
1	3.22	0.69	0.43	0.37	1.07	0.21	0.15	0.05	0.13	0.03	0.47	0.45	0.03	3.17	0.57
2	4.31	0.74	0.45	0.37	0.93	0.19	0.12	0.04	0.10	0.02	0.37	0.33	0.03	2.76	0.58
3	2.35	0.85	0.41	0.34	0.92	0.16	0.11	0.04	0.11	0.02	0.48	0.50	0.05	3.18	0.72
4	4.18	0.67	1.11	0.41	0.63	0.13	0.11	0.03	0.07	0.02	0.39	0.40	0.06	1.84	0.42
5	4.22	0.76	1.49	0.41	0.39	0.17	0.06	0.04	0.04	0.02	0.82	0.55	0.02	0.83	0.30
6	2.41	0.81	0.33	0.27	1.22	0.36	0.17	0.10	0.15	0.02	0.38	0.46	0.03	3.61	0.82
7	3.56	0.87	0.55	0.43	0.88	0.11	0.13	0.02	0.13	0.03	4.21	0.58	0.06	3.48	0.47
8	2.35	0.76	1.41	0.51	0.82	0.17	0.11	0.03	0.11	0.02	4.88	0.74	0.03	2.99	0.61
9	3.47	0.97	1.39	0.48	0.36	0.12	0.06	0.04	0.06	0.02	2.65	0.68	0.03	3.29	0.66
10	0.62	0.74	0.14	0.27	0.88	0.19	0.12	0.05	0.10	0.03	0.90	0.79	0.03	2.06	1.04
11	3.67	0.96	0.99	0.52	0.66	0.23	0.11	0.03	0.06	0.03	0.60	0.66	0.08	2.99	0.50
12	4.65	0.73	0.26	0.34	0.92	0.13	0.13	0.03	0.11	0.03	2.61	0.66	0.05	3.36	0.82
13	1.06	0.60	1.76	0.65	0.82	0.13	0.13	0.03	0.15	0.05	8.53	1.94	0.05	3.29	0.50
14	3.01	0.80	0.54	0.33	0.90	0.26	0.13	0.04	0.15	0.03	5.88	1.44	0.05	1.56	0.88
15	1.35	1.55	2.36	0.57	0.26	0.08	0.06	0.04	0.06	0.05	0.37	0.27	0.07	2.70	0.59
16	2.44	0.83	1.95	0.64	0.81	0.16	0.10	0.04	0.09	0.02	0.53	0.55	0.04	2.25	0.64
17	1.89	1.07	2.19	0.49	0.58	0.28	0.12	0.06	0.10	0.09	3.32	0.95	0.08	1.05	0.44
18	5.91	0.88	0.72	0.53	0.44	0.11	0.11	0.06	0.06	0.03	0.66	0.52	0.03	4.41	0.80
19	1.40	0.77	1.98	0.68	1.10	0.25	0.14	0.04	0.11	0.04	1.18	0.82	0.11	2.63	0.09
20	1.21	1.04	1.75	0.26	0.26	0.16	0.14	0.17	0.08	0.03	0.64	0.15	5.00	2.27	0.73
21	0.30	0.37	2.91	0.88	0.53	0.14	0.08	0.04	0.11	0.09	1.81	1.82	1.51	2.50	0.69
22	3.35	0.84	0.59	0.52	0.96	0.18	0.13	0.05	0.10	0.04	0.59	0.54	2.02	0.57	
23	2.53	0.0	0.68	0.0	1.10	0.0	0.22	0.0	0.08	0.0	0.08	0.0	5.00	0.0	
24	3.24	0.0	2.93	0.0	0.87	0.0	0.08	0.0	0.10	0.0	7.79	0.0	0.04	0.0	
25	0.71	0.0	0.01	0.0	0.65	0.0	0.13	0.0	0.19	0.0	0.08	0.0	0.01	4.55	0.0
26	0.64	0.0	1.84	0.0	0.93	0.0	0.12	0.0	0.12	0.0	0.53	0.0	3.92	0.0	
27	0.32	0.0	2.59	0.0	0.54	0.0	0.09	0.0	0.20	0.0	15.66	0.0	0.42	1.67	0.0
28	0.14	0.0	2.92	0.0	0.48	0.0	0.05	0.0	0.11	0.0	1.25	0.0	3.81	1.96	0.0

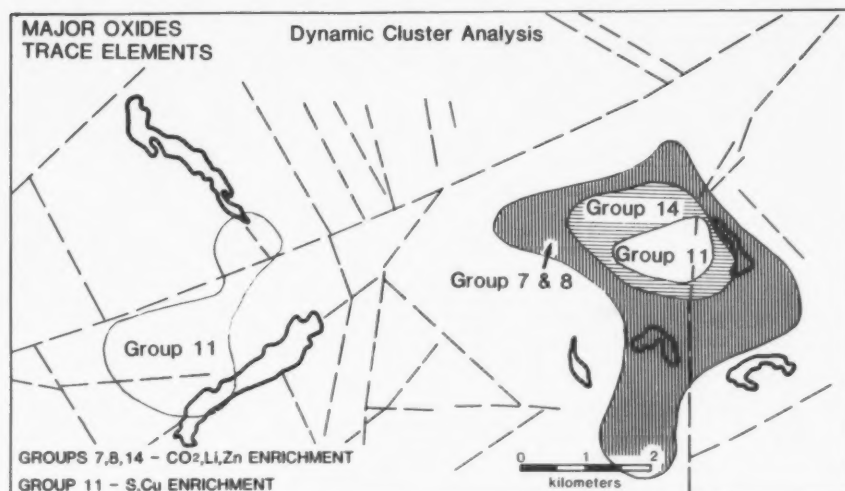


Figure 8.29a. Geographic presentation of Group 11 (S, Cu enrichment) and Groups 7, 8, and 14 (CO₂, Li, and Zn enrichment).

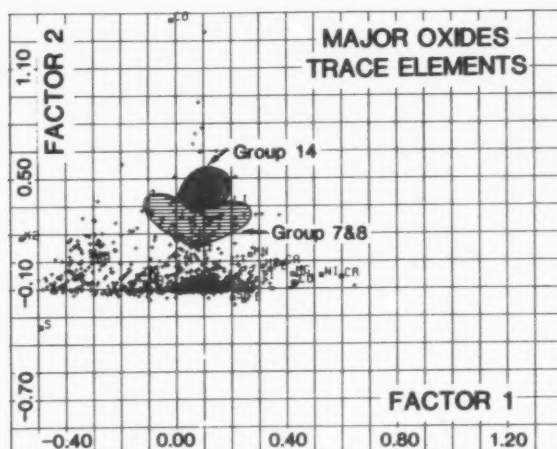


Figure 8.29b. Locations of Groups 7, 8, and 14 in the factor space.

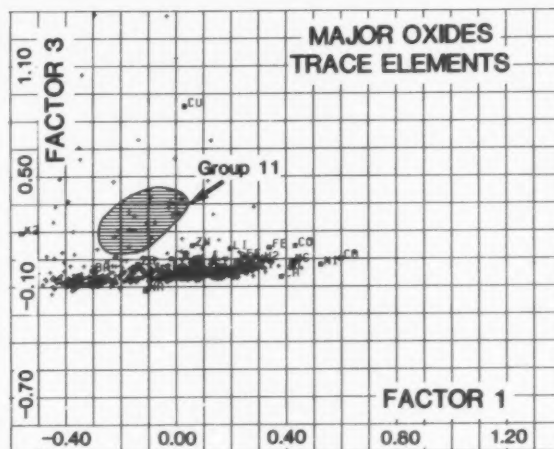


Figure 8.29c. Location of Group 11 in the factor space.

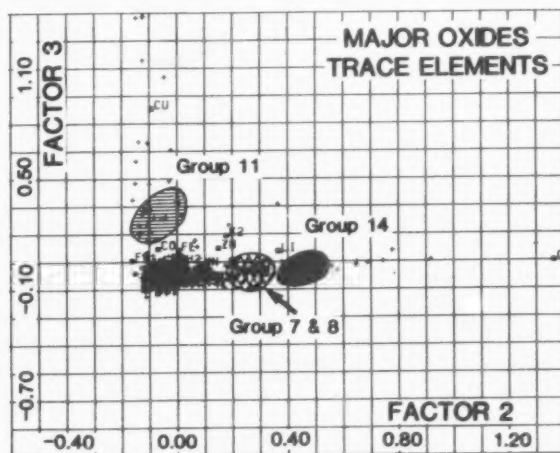


Figure 8.29d. Locations of Groups 7, 8, 11, and 14 in the factor space.

TABLE 8.4: DYNAMIC CLUSTER NUCLEII AND AVERAGE COMPOSITIONS OF EACH CLUSTER.
TABLE 8.4a. MEAN SCORES OF THE GROUPS.

GROUP	SIZE	FACTORS			
		1	2	3	4
1	115	0.136 8	-0.074 8	-0.019 3	-0.017 9
2	137	0.030 0	-0.090 8	-0.036 5	-0.064 2
3	84	0.129 2	-0.065 0	-0.023 7	0.108 3
4	58	-0.152 6	-0.086 7	-0.042 2	-0.005 0
5	37	-0.375 1	-0.044 6	-0.069 9	-0.008 4
6	55	0.256 2	-0.079 0	0.012 0	0.063 9
7	31	0.089 6	0.250 2	0.008 1	-0.004 9
8	31	0.030 7	0.292 6	0.016 3	-0.000 7
9	40	-0.317 2	0.108 8	-0.050 7	-0.009 2
10	23	0.223 6	-0.011 0	-0.035 9	-0.085 4
11	17	-0.146 7	-0.087 3	0.220 2	-0.023 9
12	45	0.034 5	0.099 6	-0.023 7	-0.101 2
13	8	0.102 3	0.653 0	0.055 5	-0.057 5
14	21	0.100 9	0.455 1	0.008 7	0.093 6
15	16	-0.402 2	-0.062 8	-0.011 2	-0.041 7
16	30	-0.034 7	-0.053 3	-0.006 4	0.175 8
17	17	-0.183 9	0.194 8	0.007 7	0.113 9
18	27	-0.291 2	-0.074 3	-0.084 0	0.102 0
19	8	0.082 7	0.003 8	0.072 8	-0.097 9
20	3	-0.208 2	-0.131 9	1.378 7	0.247 9
21	6	-0.398 7	-0.037 1	0.448 7	-0.138 3
22	7	0.025 9	-0.105 2	0.521 6	0.144 3
23	1	0.210 6	-0.185 2	1.469 0	-0.123 9
24	1	-0.194 6	0.578 3	0.004 9	-0.296 4
25	1	0.645 4	-0.086 0	0.086 0	0.026 5
26	1	-0.000 3	-0.124 6	1.143 8	0.319 2
27	1	0.106 4	1.299 4	0.135 3	0.054 5
28	1	-0.340 1	-0.045 1	1.052 8	-0.115 9
					0.106 2

TABLE 8.4b: DYNAMIC CLUSTER ANALYSIS: GROUP DESCRIPTION.

Group	MEAN VALUES & STANDARD DEVIATIONS (S.D.)										MgO	S.D.	CaO	S.D.
	SiO ₂	S.D.	Al ₂ O ₃	S.D.	Fe ₂ O ₃	S.D.	FeO	S.D.	7 Al ₂ O ₃	S.D.				
1	540 489.57	17 685.10	163 790.43	9 699.36	22 139.13	4 065.42	59 295.65	7 411.92	55 381.74	6 263.69	67 815.65	10 027.26		
2	574 956.93	21 706.98	162 643.80	12 134.78	18 685.40	4 742.77	50 144.53	8 025.13	47 541.61	8 604.95	51 204.38	10 976.93		
3	550 823.81	21 902.98	168 008.33	11 300.38	20 332.14	3 959.38	49 207.14	7 685.96	42 363.10	7 987.49	89 475.00	11 568.36		
4	640 134.48	23 943.72	157 898.28	14 222.96	16 665.52	4 317.39	31 575.86	6 899.31	27 689.66	8 853.88	39 765.52	12 440.97		
5	733 021.62	27 292.05	135 572.97	10 359.98	8 859.46	4 641.45	15 372.97	6 809.66	6 483.78	2 481.77	18 323.73	6 909.97		
6	505 298.16	25 331.09	159 261.82	13 855.08	25 447.27	2 883.02	76 374.55	9 231.73	71 785.45	13 313.98	74 647.27	14 908.79		
7	533 474.16	22 673.64	151 677.42	8 099.33	13 970.97	3 666.99	59 125.81	7 934.65	53 477.42	6 612.20	54 648.39	6 514.64		
8	554 941.94	75 783.72	146 258.06	17 745.89	13 980.65	7 703.78	51 787.10	7 032.05	37 132.26	17 204.52	69 429.03	23 370.61		
9	711 085.00	31 166.75	128 460.00	13 513.60	8 395.00	4 424.12	20 382.50	7 032.05	8 057.50	3 580.21	31 117.50	5 994.48		
10	535 643.48	33 633.13	163 386.96	14 609.07	21 743.48	3 553.85	44 152.17	10 621.29	32 926.09	9 775.07	137 804.35	15 684.13		
11	630 670.59	62 041.50	150 411.76	21 393.10	19 929.41	3 724.54	36 429.41	19 984.99	33 823.53	7 240.31	34 223.53	16 939.88		
12	560 417.78	20 650.15	155 573.33	8 850.33	16 473.33	5 150.57	51 548.89	9 563.73	45 940.00	9 403.04	49 802.22	13 289.53		
13	504 462.50	15 543.94	141 800.00	10 728.73	9 312.50	3 492.62	60 975.00	9 563.73	53 900.00	9 403.04	67 912.50	7 812.52		
14	522 433.33	25 436.77	140 738.10	10 814.13	9 795.24	3 167.09	56 928.57	5 946.61	50 447.62	8 263.51	70 804.76	14 387.23		
15	765 406.25	35 372.88	122 775.00	17 123.30	8 325.00	4 242.56	20 293.75	12 839.70	12 793.75	8 947.59	5 693.75	4 758.78		
16	588 066.67	30 555.18	165 666.67	11 835.11	17 860.00	3 437.08	43 516.67	7 237.26	40 420.00	9 617.92	54 586.67	15 275.04		
17	638 241.18	46 244.34	146 664.71	20 135.17	9 505.88	5 756.14	33 400.00	9 170.40	22 676.47	6 694.73	41 088.24	7 232.90		
18	688 444.44	34 872.06	152 118.52	14 198.54	10 281.48	4 773.42	74 425.00	8 718.17	11 988.89	5 881.54	21 581.48	8 203.47		
19	537 597.50	25 421.28	168 775.00	11 626.66	19 137.50	1 558.85	72 766.67	13 283.58	60 350.00	8 776.43	30 250.00	20 876.92		
20	605 766.67	99 416.31	124 833.33	43 707.25	17 600.00	3 463.33	20 266.67	3 181.72	37 533.33	17 811.89	18 333.33	24 046.69		
21	723 316.67	44 548.73	126 733.33	16 304.31	18 333.33	2 802.38	59 142.86	7 456.99	11 750.00	4 679.64	12 366.67	9 814.21		
22	548 157.14	56 068.91	158 214.29	10 509.90	24 000.00	0.0	149 400.00	21 648.39	47 957.14	10 567.54	56 571.43	27 782.35		
23	399 200.00	0.0	153 500.00	0.0	26 100.00	0.0	34 000.00	0.0	24 800.00	0.0	76 500.00	0.0		
24	567 400.00	0.0	167 800.00	0.0	9 100.00	0.0	111 000.00	0.0	13 600.00	0.0	49 900.00	0.0		
25	426 900.00	0.0	95 400.00	0.0	21 700.00	0.0	115 700.00	0.0	194 100.00	0.0	74 800.00	0.0		
26	521 200.00	0.0	157 000.00	0.0	24 100.00	0.0	20 500.00	0.0	45 600.00	0.0	3 800.00	0.0		
27	464 800.00	0.0	102 100.00	0.0	1 700.00	0.0	53 100.00	0.0	38 100.00	0.0	155 600.00	0.0		
28	670 100.00	0.0	115 300.00	0.0	19 700.00	0.0	53 100.00	0.0	14 300.00	0.0	17 600.00	0.0		

TABLE 8.4b: CONTINUED.

Group	Na ₂ O	S.D.	K ₂ O	S.D.	MEAN VALUES & STANDARD DEVIATIONS (S.D.)								MnO	S.D.	CO ₂	S.D.
					TiO ₂	S.D.	P ₂ O ₅	S.D.	137.39	541.52	1246.96	260.00				
1	32 931.30	6 400.90	4 273.04	3 651.25	10 536.52	2 077.59	1 437.39	541.52	1 246.96	260.00	4 780.00	4 503.82				
2	43 481.02	7 374.21	4 334.31	3 674.26	9 370.07	1 914.20	1 237.23	429.09	1 059.85	197.58	3 772.26	3 330.00				
3	23 408.33	8 570.86	4 063.10	3 350.55	9 233.33	1 622.53	1 073.81	433.01	1 073.81	192.08	4 786.90	5 013.49				
4	41 453.45	6 564.42	11 270.69	4 561.93	6 379.31	1 381.04	1 110.34	337.53	724.14	205.46	3 820.69	3 989.58				
5	42 240.54	7 595.59	14 918.92	4 055.10	3 921.62	1 673.67	567.57	437.83	416.22	204.82	8 200.00	5 510.39				
6	24 145.45	7 993.93	3 703.64	3 168.71	12 260.00	3 377.24	1 720.00	929.64	1 498.18	218.15	3 796.36	4 419.32				
7	35 603.23	8 678.54	5 538.71	4 291.52	8 803.23	1 233.53	1 277.42	223.17	1 293.55	288.60	42 093.55	8 535.26				
8	26 209.68	13 264.22	11 538.71	6 743.33	8 280.65	3 254.58	1 141.94	494.49	1 270.97	496.11	25 037.50	5 004.49				
9	32 987.50	7 985.12	14 472.50	2 650.81	8 786.96	1 935.39	1 182.61	453.92	630.00	180.03	9 034.78	7 901.70				
10	6 247.83	7 383.76	1 395.65	5 229.96	6 605.88	2 260.94	1 129.41	280.10	1 017.39	255.22	6 041.18	6 569.92				
11	36 729.41	9 558.75	9 900.00	3 414.91	9 208.89	1 275.79	1 273.33	325.02	617.65	318.66	26 071.11	6 557.84				
12	46 484.44	7 339.90	2 580.00	6 528.39	8 175.00	1 343.50	1 337.50	266.93	1 097.78	461.17	85 350.00	19 374.80				
13	10 625.00	6 034.60	17 562.50	3 087.17	8 014.29	967.10	1 185.71	272.55	1 404.76	233.40	64 657.14	9 644.72				
14	32 028.57	6 391.88	6 319.05	5 695.01	2 575.00	847.35	575.00	399.17	575.00	450.92	3 731.25	2 724.39				
15	13 475.00	15 463.87	23 587.50	6 417.83	8 000.00	1 603.66	963.33	366.23	933.33	174.86	5 246.67	5 549.76				
16	24 353.33	8 306.28	19 090.00	4 889.03	5 770.59	2 780.91	1 188.24	585.11	1 041.18	906.27	33 211.76	9 512.88				
17	18 900.00	10 715.47	21 947.06	5 345.02	4 425.93	1 085.43	1 059.26	640.47	588.89	254.70	6 633.33	5 189.12				
18	59 125.93	8 836.79	7 218.52	6 759.21	11 037.50	2 457.02	1 375.00	373.21	1 125.00	369.36	11 825.00	8 186.53				
19	14 025.00	7 720.61	19 787.50	2 598.08	2 600.00	1 558.85	1 433.33	1 703.92	833.33	288.68	6 433.33	1 514.38				
20	12 100.00	10 407.21	17 500.00	8 370.11	4 966.67	1 490.86	733.33	403.32	766.67	575.04	9 300.00	7 299.86				
21	1 016.67	890.88	31 933.33	5 164.12	9 600.00	1 787.92	1 257.14	509.43	1 014.29	445.08	5 914.29	5 356.44				
22	33 457.14	8 365.56	5 914.29	0.0	11 000.00	0.0	2 200.00	0.0	800.00	0.0	800.00	0.0				
23	25 300.00	0.0	6 800.00	0.0	8 700.00	0.0	800.00	0.0	1 000.00	0.0	77 900.00	0.0				
24	32 400.00	0.0	29 300.00	0.0	8 700.00	0.0	1 300.00	0.0	1 900.00	0.0	800.00	0.0				
25	7 100.00	0.0	100.00	0.0	6 500.00	0.0	1 200.00	0.0	1 200.00	0.0	5 300.00	0.0				
26	6 400.00	0.0	18 400.00	0.0	9 300.00	0.0	900.00	0.0	2 000.00	0.0	156 600.00	0.0				
27	3 200.00	0.0	25 900.00	0.0	5 400.00	0.0	500.00	0.0	1 100.00	0.0	12 500.00	0.0				
28	1 400.00	0.0	29 200.00	0.0	4 800.00	0.0	500.00	0.0	1 100.00	0.0	0.0	0.0				

TABLE 8.4b: CONTINUED.

Group	S	MEAN VALUES & STANDARD DEVIATIONS (S.D.)						Cr	Cu	S.D.
		S.D.	H ₂ O+	S.D.	Ba	S.D.	Co	S.D.		
1	240.87	465.27	31 630.43	5 451.59	168.35	94.73	29.65	5.60	48.22	26.13
2	299.27	550.47	27 670.80	5 620.47	162.34	91.42	26.06	4.26	52.49	52.08
3	540.48	1 101.38	31 876.19	7 278.28	140.37	75.63	26.64	5.83	50.45	20.03
4	598.28	898.24	18 212.07	4 103.79	267.93	132.17	14.50	5.19	60.26	112.95
5	237.84	250.94	8 283.78	2 998.47	344.59	136.27	3.74	2.24	12.89	15.08
6	361.82	800.58	35 247.27	8 330.15	150.55	95.65	38.11	7.72	56.38	27.02
7	645.16	742.45	34 825.81	4 687.07	159.35	85.24	24.90	5.70	52.40	46.49
8	970.97	2 573.35	28 270.97	11 573.54	258.71	146.71	22.84	11.42	54.74	50.39
9	312.50	655.23	11 367.50	4 232.92	254.75	107.13	4.21	2.56	12.20	9.99
10	330.43	356.03	32 856.52	6 591.88	76.96	36.36	23.83	4.76	54.04	28.39
11	9 817.65	2 894.01	20 641.18	10 420.96	252.94	187.31	19.38	12.05	183.69	313.23
12	544.44	1 095.56	29 868.89	4 983.97	126.22	94.54	25.42	4.64	39.27	31.68
13	462.50	794.51	33 600.00	8 233.38	306.25	164.57	23.38	4.10	37.38	14.44
14	519.05	725.69	31 538.10	3 942.14	177.62	90.93	23.29	3.23	52.62	64.57
15	737.50	1 096.59	15 600.00	8 829.50	450.62	245.21	3.38	2.45	17.00	14.28
16	410.00	684.48	27 120.00	5 764.54	450.00	214.88	21.97	5.06	70.40	97.37
17	800.00	1 030.17	22 523.53	6 369.31	389.41	134.00	11.41	7.19	53.53	67.81
18	292.59	398.97	10 507.41	4 364.41	217.78	149.11	6.41	2.97	25.31	54.69
19	1 125.00	2 899.63	44 150.00	8 019.80	355.00	154.64	27.13	7.79	44.63	26.77
20	50 000.00	0.0	26 333.33	929.16	126.67	40.41	15.67	22.81	473.30	456.05
21	16 633.33	5 319.65	18 883.33	1 801.57	210.00	97.16	12.25	5.74	376.15	438.79
22	20 228.57	5 692.31	25 028.57	6 896.31	137.71	67.60	29.71	16.33	186.41	359.37
23	50 000.00	0.0	28 300.00	0.0	150.00	0.0	155.00	0.0	999.90	0.0
24	400.00	0.0	3 000.00	0.0	480.00	0.0	13.00	0.0	56.00	0.0
25	100.00	0.0	45 500.00	0.0	60.00	0.0	88.00	0.0	36.00	0.0
26	39 200.00	0.0	48 300.00	0.0	280.00	0.0	30.00	0.0	220.00	0.0
27	4 200.00	0.0	16 700.00	0.0	280.00	0.0	10.00	0.0	106.00	0.0
28	38 100.00	0.0	19 600.00	0.0	120.00	0.0	28.00	0.0	48.00	0.0

TABLE 8.4b: CONTINUED.

Group	MEAN VALUES & STANDARD DEVIATIONS (S.D.)											
	Li	S.D.	Ni	S.D.	Zn	S.D.	Sr	S.D.	V	S.D.	Y	S.D.
1	14.76	4.07	110.07	31.22	85.05	17.22	171.91	73.22	173.17	59.72	25.03	10.31
2	14.40	5.62	95.87	29.41	81.09	28.58	130.87	66.03	156.50	56.44	22.23	9.58
3	13.88	3.77	90.89	27.12	74.14	17.92	157.69	90.91	177.56	50.70	21.96	7.73
4	11.78	4.32	39.74	28.57	70.02	22.62	167.76	98.49	90.17	39.45	24.09	15.75
5	6.99	4.16	3.15	1.56	47.11	23.11	85.59	39.02	15.73	18.58	31.86	11.29
6	17.67	7.08	138.69	58.98	110.44	64.31	188.73	70.93	190.84	52.66	26.24	10.00
7	41.65	17.43	102.08	30.39	120.35	165.86	94.84	28.03	149.68	39.37	18.87	4.26
8	24.89	14.29	76.73	45.03	113.48	169.72	95.81	61.74	122.77	83.14	20.19	11.32
9	10.24	4.92	3.15	2.02	49.75	26.08	70.00	31.70	16.43	17.79	32.75	13.98
10	11.26	3.90	77.17	29.30	71.00	21.11	172.91	187.27	190.22	61.38	24.00	8.26
11	16.18	11.10	54.15	45.06	70.00	38.08	131.47	83.62	92.06	62.48	22.59	13.47
12	26.27	11.87	100.56	30.85	96.78	121.96	133.56	68.69	152.56	49.72	21.42	7.19
13	45.00	7.23	85.00	27.75	121.62	66.94	77.50	43.59	121.25	55.15	16.63	8.52
14	39.67	10.28	109.29	16.92	97.19	38.04	85.00	30.66	126.19	40.18	18.43	5.89
15	11.97	8.03	3.31	2.34	243.56	306.45	45.06	38.96	5.72	5.14	29.25	17.15
16	14.53	5.10	72.50	35.07	75.00	24.51	159.63	102.83	138.67	49.96	20.93	8.33
17	22.47	12.99	21.09	23.68	90.53	65.44	81.47	41.45	66.00	46.38	23.00	13.82
18	8.02	4.03	8.59	7.94	56.15	32.83	134.63	81.89	31.81	27.83	35.74	20.83
19	35.75	14.12	97.63	32.05	247.11	309.17	86.88	34.12	173.12	42.00	19.13	11.58
20	27.00	6.08	31.67	50.52	27.53	45.44	96.67	47.26	86.67	141.45	31.67	7.64
21	8.67	2.07	31.92	21.75	228.50	368.88	29.50	39.88	55.83	38.52	21.83	16.02
22	13.86	5.49	76.50	42.55	89.29	38.52	123.57	75.92	132.14	98.57	26.14	16.85
23	12.00	0.0	110.00	0.0	63.00	0.0	600.00	0.0	100.00	0.0	15.00	0.0
24	6.00	0.0	38.00	0.0	45.00	0.0	140.00	0.0	150.00	0.0	12.00	0.0
25	10.00	0.0	770.00	0.0	85.00	0.0	70.00	0.0	150.00	0.0	15.00	0.0
26	55.00	0.0	78.00	0.0	1.10	0.0	60.00	0.0	150.00	0.0	15.00	0.0
27	16.00	0.0	34.00	0.0	999.90	0.0	70.00	0.0	90.00	0.0	20.00	0.0
28	10.00	0.0	49.00	0.0	101.00	0.0	4.00	0.0	65.00	0.0	12.00	0.0

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